

**END POINT CARBON AND TEMPERATURE  
PREDICTION USING SUBLANCE MEASUREMENTS  
IN OXYGEN STEELMAKING CONVERTERS**

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by

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to the

**DEPARTMENT OF MATERIALS AND**

**METALLURGICAL ENGINEERING**

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## CERTIFICATE

It is certified that the work contained in the thesis entitled **End point carbon and Temperature prediction using substance measurements in oxygen Steelmaking Converters**, by Annabhimoju Sateesh Kumar, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.



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## ABSTRACT

Oxygen steelmaking converter is the single most important unit process in a steel plant and is some times called the throbbing heart of a steel plant. Introduction of sub lance technology in the early eighties to analyze carbon and temperature in an oxygen steelmaking converter during the blow but approximately 3-4 minutes before the end blow proved to be an important step in the control of oxygen steelmaking processes. Since the introduction of sub lance, the accuracy of end point prediction (hit rate) at most of the steel plants has gradually increased from approximately 60% to 90%. The efforts are now being made to narrow down the range of end point carbon and temperature, known as carbon window and temperature window. Several models have been reported in literature and these are critically reviewed.

It is generally agreed that the rate limiting step for oxidation of carbon is mass transfer in metal phase. However, it has been hard to isolate as to which is rate controlling : the mass transfer in bulk metal or the mass transfer in metal droplets ejected from jet impact zone. In the present work both the possibilities are investigated by developing a new model based on mass transfer control in which the operational factors like lance height, time of blow, coolant additions, slag volume, slag basicity, etc are also incorporated. Exhaustive operational data collected from four different plants are analyzed and a comparative evaluation of different models has been done to find out the suitability of different types of models. The average end point carbon lies in the range of 0.035-0.06 % and average end point temperature lies in the range of 1600-1660 °C. It is now possible to predict end point carbon within  $\sigma = \pm 8$  milli percent and temperature within  $\sigma = \pm 8$  °C with the help of models developed in the present work.



*Dedicated to*  
*my Parents*

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# List of Symbols

$a$	: radius of the droplet (mm)
$a_0, a_1$	: coefficient of oxygen balance
$a_C$	: activity of carbon in hot metal.
$a_{Fe}$	: activity of Iron
$a_{FeO}$	: activity of Feo
$A$	: interfacial area (cm <sup>2</sup> )
$b_o, b_2$	: coefficient of heat balance .
$C_c$	: wt % of carbon in the melt
$[\%C]$	: weight percent of carbon
$C^b, C^i$	: bulk and interfacial concentration of carbon, mol/cc
$C_p$	: specific heat capacity of molten steel (Kcal / °K)
$C_B$	: carbon content of bulk charge ( wt %)
$C_f$	: carbon content of the bath at blowing end (wt %)
$C_{SL}$	: carbon content of the bath measured by the sensor lance (wt % )
$C_0$	: critical carbon content below which decarburization does not substantially occur ( milli percent )
$C_p$	: parameter derived statistically based on operational variables.



$C_S$	: bulk concentration of sulphur (wt %)
$C_{EP}$	: carbon content at endpoint (milli percent )
$D$	: diffusivity of carbon ( $m^2/s$ )
erro(i)	: error of the feedback model
$f$	: $\gamma_s^b / \gamma_s^k$ activity coefficient of sulphur in the surface layer and in bulk metal.
$f_i$	: input oxygen ( $m^3$ )
$f_o$	: output oxygen ( $m^3$ )
$F$	: amount of coolant and flux (kg)
$F$	: F – test value in the regression
$F_{O_2}$	: the amount of oxygen after sublimance measurement ( $m^3$ )
$FB_C$	: adjustment of oxygen balance from the feedback ( $m^3$ )
$F_{BT}$	: adjustment of heat balance from the feedback
$F_{t+1}$	: the forecast value for the next period
$FB(i)$	: feedback value
$G$	: gain
$G_{FB}$	: feedback gain
$h_o$	: output carbon
$h_i$	: input carbon
$H$	: on-detective value
$k_g$	: average mass transfer coefficient in gas film (m/sec)
$k_R$	: rate constant ( $mol/m^2/sec/atm$ )
$K$	: adsorption coefficient of Sulphur
$k_C, k_d$	: mass transfer coefficient (m/sec)
$l_i$	: coefficient of statistical model
$Mdlerro(i)$	: error of the model

- $m$  : constant of sampling number
- $m$  : slope of regression curve
- $N$  : the number of historical data.
- $n_c$  : concentratin of carbon (b: bulk, i: interfacial)
- $O_c$  : oxygen combined with carbon to form CO ( $Nm^3 - O_2$ )
- $O_{CO}$  : oxygen combined with CO to form  $CO_2$  ( $Nm^3 - O_2$ )
- $O_{Fe}$  : oxygen combined with Fe to form FeO ( $Nm^3 - O_2$ )
- $P$  : parameters calculated from multiple regression analysis by using actual operational data such as lance height, slag volume, etc.
- $P_{CO_2}^b$  : bulk pressure of  $CO_2$  (atm)
- $P_{CO_2}^i$  : interfacial pressure of  $CO_2$  (atm)
- $P_{CO}$  : partial pressure of cabon monoxide
- $P_{CO_2}$  : partial pressure of carbon dioxide
- $P_{O_2}$  : partial pressure of oxygen
- $Q$  : parameters calculated from multiple regression analysis by using actual operational data such as lance height, slag volume , etc.
- $QB$  : bottom blowing gas flow rate ( $m^3/s$ )
- $R$  : correlation coefficient in the regression
- $R$  : parameters calculated from multiple regression analysis by using actual operational data such as lance height, slag volume, etc.
- $R_c$  : rate of carbon transfer (mol / sec)
- $s_1, s_2$  : coefficients
- $Si_B$  : silicon content of charge (%)

$(T.Fe)_s$	: (T. Fe) at in - blow subllance
$T_{SL}$	: temperature at subllance measurement (K)
$T_{EP} , T_f$	: temperature at the endpoint (K)
$T_{sub}$	: cooling capacity of fluxes
$V$	: CO, CO <sub>2</sub> volume in exhaust gas (m <sup>3</sup> )
$V_{C,I}$	: rate of carbon oxidation (%C/min)
$WM$	: weight of steel (tons)
$W_{so}$	: slag volume except (FeO), (MnO) , (P <sub>2</sub> O <sub>5</sub> )
$W_s$	: slag volume
$W_t$	: bath weight in gms
$WO_2$	: oxidation degree
$W_{sub}$	: amount of flux (kg)
$W_{ST}$	: weight of molten steel (kg)
$X_i$	: factor i of operating condition of steel
$X_t$	: the most recent observation
$\bar{\bar{X}}_i$	: mean value of $X_i$
$Z_i$	: operational variables
$\bar{Z}_i$	: standard operational variables (mean values )
$\alpha$	: decarburization efficiency
$\alpha , \beta , \gamma , \delta$	: parameter
$\alpha_{max}$	: decarburization efficiency in maximum decarburization period
$\gamma$	: coefficient of cooling capacity
$\gamma_i$	: regression coefficient
$\gamma_0$	: regression Constant

- $\varepsilon$  : sensitivity factor
- $\xi$  : theoretical maximum decarburization rate (%/sec)
- $\eta$  : coefficient of oxygen in fluxes
- $\chi_i, \varepsilon_i$  : regression coefficients
- $\chi_0$  : constant
- $\rho$  : density of the melt ( $\text{g/cm}^3$ )
- $\sigma$  : standard deviation
- $\lambda_i, \mu_i$  : coefficients.
- $\theta_u$  : the fraction of the surface sites not available for the chemisorption of sulfur.
- $\theta_s$  : the fraction of surface sites occupied by sulphur
- $\Delta C$  : amount of decarburization
- $\Delta O_2$  : the amount of oxygen required (per ton of charge) to reduce the carbon content from  $C_{SL}$  to  $C_{La}$  ( $\text{Nm}^3/\text{ton of charge}$ )
- $\Delta C_i$  : the change of steel carbon content and  $\Delta O_i$  is the amount of oxygen during the sampling period  $\Delta t$  as shown below. .
- $\Delta H_i$  : the heat produced from each reaction ( $\text{Kcal} / \text{Nm}^3 - O_2$ )

# **CHAPTER 1**

## **OXYGEN STEELMAKING PROCESS AND THE SUBLANCE**

### **1.0 Introduction**

Oxygen steel making process accounts for approximately 65% of the steel produced in the world. A typical diagram of the physical state of an oxygen steelmaking converter is shown in Fig 1. The pure oxygen jet emerging from the lance, placed at center of vessel, impinges on metal surface. A stream of metal droplets is ejected due to deflection of the jet in the impingement zone. The droplets eventually fall back to metal after their passage through slag. The amount and size range of the droplets depend on lance nozzle design and lance height whereas the residence time of droplets in slag depends upon the properties of slag. The chemical reactions occur primarily in the jet impact zone and in the droplets falling through slag.

In the early stages of its developments, oxygen steelmaking process itself was given several names like LD (Linz-Donavitz), BOF (Basic Oxygen Furnace), BOP (Basic Oxygen Process), BOS (Basic Oxygen Steelmaking), etc. These names were modified when bottom blowing process was invented in which the oxygen gas was blown through tuyeres located at the bottom of the converter. The tuyeres needed cooling

because of the high temperature generated at the tuyere tip. Depending upon the nature of coolant used (viz. fuel oil or natural gas), the new breed of processes were named as Q-BOP, LWS, etc. As a further modification of bottom blowing practice, combined top and bottom blowing processes were invented and today more than 30 commercial names exist for the variety of oxygen steelmaking processes. For the sake of simplicity, however, they all are now grouped under a single name of 'Combined blown processes'.

The specific combination of top and bottom blowing (i.e. the flowrate and nature of gas through top and/or bottom) adopted at a particular plant depends upon the starting composition of hot metal, capacity of converter, quality of lime, refractory life, desired end point composition of steel, economies of operation, etc. As a result, the steelmaking process at each steel plant has its own unique features and the control models developed at one plant are rarely applicable to the situation at another steel plant. In a more recent development (mid eighties), a separate lance called "Sublance" is introduced into the converter to measure temperature and take a sample of metal, approximately 3-4 minutes before the end of the blow. Corrective actions are then taken based on analysis of sample obtained by sublance measurement and this has significantly improved the accuracy of control of obtaining desired end point temperature and carbon of liquid steel. The fine tuning models so developed are called "sublance models".

## **1.1 Scope of Present Work**

The objective of the present work is to develop sublance models (as described above) for the prediction of end point temperature and carbon of liquid steel. Different models available in literature are reviewed in Chapter 2 and tested on operational data in

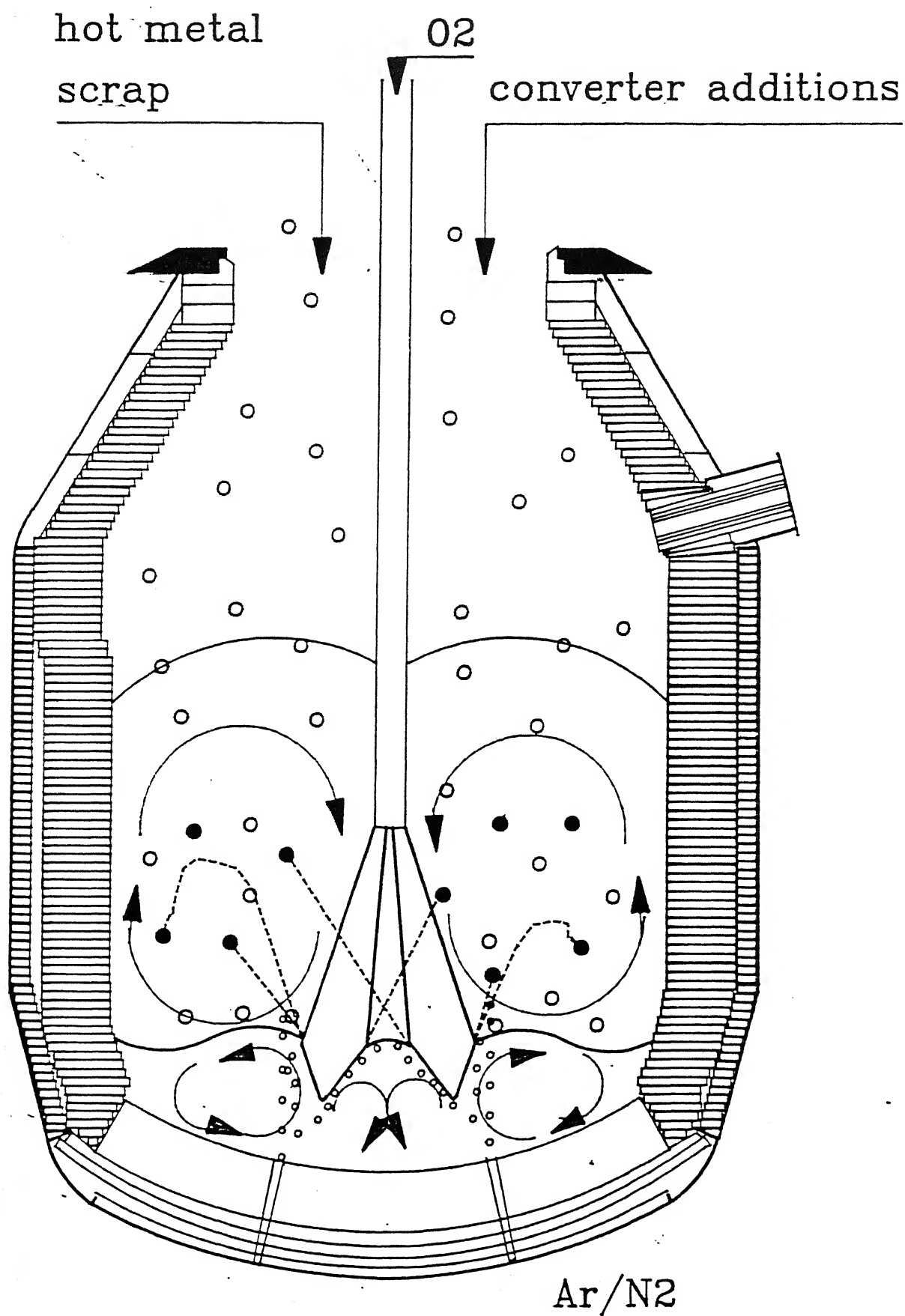


Fig. 1. Oxygen steelmaking converter process

Chapter 3. A new model is also developed in the present work based on the assumption that decarburization primarily occurs in the recirculation zone of jet impingement. Data have been obtained from different steel plants (Chapter 3) to compare if the same nature of variables can be used to characterize the last stages of oxygen steelmaking process. The contribution of droplets to decarburization vis a vis the decarburization in recirculation zone and the performance of different models is also discussed in Chapter 3. The main conclusions of the investigation are summarized in Chapter 4 along with suggestions for further work.



## **CHAPTER 2**

### **REVIEW OF MODELS FOR END POINT CARBON AND TEMPERATURE PREDICTION USING SUBLANCE DATA**

#### **2.0 Introduction**

One of the key objectives during end blow period (i.e. the period after sublance measurement) is the control of decarburization rate. A lot of research has been done in this area and several models, both static and dynamic, have been proposed which are suited to specific steel plant conditions. A brief summary of the fundamental basis of various models based on sublance measurements is presented in section 2.1 to section 2.5.

#### **2.1 Model by Lee and Rao**

Lee and Rao [1] have developed a mixed control model for decarburization in levitated droplets assuming gas phase mass transfer and dissociative adsorption of  $\text{CO}_2$  (or interfacial chemical reaction) by studying the kinetics of decarburization in high carbon regime (0.911 - 2.479 wt % C) at 1973 K. The rate equation assuming mass transfer control in the gas phase as

$$\frac{-dc_c}{dt} = \frac{1200.A}{\rho V} \cdot \frac{k_g}{RT_f} \ln(1 + P^b_{CO_2}) \quad (2.1)$$

where,

$C_c$  = wt % of carbon in the melt

$A$  = interfacial area ( $\text{cm}^2$ )

$\rho$  = density of the melt ( $\text{g/cm}^3$ )

$V$  = Volume of the melt ( $\text{cm}^3$ )

$k_g$  = average mass transfer coefficient in gas film ( $\text{cm/sec}$ )

$T_f$  = average gas film temperature ( $^{\circ}\text{K}$ )

$P^b_{CO_2}$  = bulk pressure of  $\text{CO}_2$ . (atm)

If interfacial chemical reaction control is assumed as a rate controlling step, then

$$\frac{-dC_c}{dt} = \frac{1200.A}{\rho V} k_R \left( \frac{1 + K\theta_u f C_s}{1 + Kf C_s} \right) P^i_{CO_2} \quad (2.2)$$

where,

$k_R$  = rate constant ( $\text{mol/m}^2/\text{sec/atm}$ )

$K$  = adsorption coefficient of Sulphur

$\theta_u$  = the fraction of the surface sites not available for the chemisorption of sulfur

$f$  =  $\gamma^b_s / \gamma^k_s$  activity coefficient of sulphur in the surface layer and in bulk metal.

$C_s$  = bulk concentration of sulphur (wt %)

$P_{CO_2}^i$  = interfacial pressure of  $CO_2$ .

On assuming mixed control of mass transfer and interfacial chemical reaction, the decarburization rate is

$$\frac{-dC_c}{dt} = \frac{1200A}{\rho V} \cdot \frac{k_g^0 k_R (1 + K \theta_u f C_s)}{(k_g^0 + k_R) + (k_g^0 + k_R \theta_u) K f C_s} \ln(1 + P_{CO_2}^b) \quad (2.3)$$

where,

$$k_g^0 = \frac{k_g}{R.T_f}$$

The experimental results of Lee and Rao showed that

- Liquid phase mass transfer is not a rate controlling step in the high carbon regime. The initial carbon concentration has no discernible effect on the decarburization kinetics.
- Sulphur has a clear and reproducible retarding effect on decarburization. This effect is most pronounced in the range of 0 to 0.05 mass % sulphur.
- The  $P_{CO_2}$  of the gas mixture has a marked effect on the decarburization kinetics.
- The flow rate of the gas mixture has a small but finite effect on the rate of decarburization.

In low carbon range ( $C < 0.4$  mass %) equation assuming liquid phase mass transfer as control step is

$$R_c = \frac{k_c A}{V} (n_c^b - n_c^i) \quad (2.4)$$

where,

$R_c$  = rate of carbon transfer (mol / sec)

$k_c$  = mass transfer coefficient of carbon (m/sec)

$n_c$  = concentratin of carbon (b=bulk, i=interface )

Distin, Hallett and Richardson [2] have assumed in their study on the decarburization of liquid Fe-C alloys with  $O_2$  and CO -  $CO_2$  mixtures that the concentration of carbon at the surface becomes virtually zero at the instant of oxide formation. When the oxide appears on the surface Eq. (2.4) is reduced to

$$R_c = \frac{k_c A}{V} n_c^b.$$

$$\text{Or } \frac{-d[\%C]}{dt} = \frac{k_c A}{V} (\%C^b) \quad (2.5)$$

where,

A = Surface area of droplet ( $m^2$ )

V = Volume of droplet ( $m^3$ )

For spherical droplets [1]

$$k_c = \frac{5D}{a} \quad (2.6)$$

where,

D = diffusivity of carbon

a = radius of the droplet

Lee and Rao calculated the  $k_c$  for their experimental conditions as follows:

T = 1973K

$$C^b = 0.1\%$$

$$a = 0.2875 \text{ cm}$$

$$D = 3.24 \times 10^{-3} \text{ cm}^2/\text{sec}$$

$$k_c = \frac{5D}{a} = \frac{5 \times 3.24 \times 10^{-3}}{0.2875} = 56.348 \times 10^{-3} \text{ cm/sec}$$

$$= 56.348 \times 10^{-5} \text{ m/sec}$$

They found that mass transfer in the liquid phase is enhanced by about ten times due to electromagnetic levitation as compared to that at stationary condition. This enhancement is brought about as a consequence of motion in the liquid phase. A situation, similar to those for levitated droplets, may be assumed to prevail during decarburization in converter where droplets are ejected from jet impact zone at high velocity.

## 2.2 Model by Chou et al.

Chou, Pal and Reddy [3] have developed a general model for the decarburization process. If it is assumed that hot metal at  $1400^\circ\text{C}$  with a high carbon content is initially charged (for instance, liquid iron containing 4% carbon) in the converter with some scrap, then for the sake of simplicity bath temperature may be approximated to vary linearly with carbon content as follows:

$$T = 1873 - 50 [\% \text{ C}] \quad (2.7)$$

where,

$T$  = the absolute temperature of the bath

$[\% \text{ C}]$  = carbon concentration in the bath expressed in wt. pct.

In an actual converter, bath temperature can be predicted at each time step by dynamic heat and mass balance. When oxygen blows into the liquid metal, the carbon in hot

metal will be oxidised by oxygen to form carbon dioxide. At an elevated temperature, the  $\text{CO}_2$  will react again with bath carbon according to the Boudouvard reaction



where,

$[\text{C}]$  = the carbon dissolved in the hot metal.

In accordance with the mass action law, we have

$$K = \frac{P_{\text{CO}}^2}{P_{\text{CO}_2} \cdot a_{\text{C}}} \quad (2.9)$$

where,

$P_{\text{CO}}, P_{\text{CO}_2}$  = the partial pressure of CO and  $\text{CO}_2$  respectively.

$a_{\text{C}}$  = activity of carbon in hot metal.

$K$ , the Equilibrium constant, is a function of temperature and can be derived in terms of standard Gibbs free energy data.

$$K = \exp [15.30 - (16759/T)] \quad (2.10)$$

Substituting Eq (2.7) into Eq (2.10) and combining with Eq (2.9) yield

$$\exp \left[ 15.30 - \frac{16759}{1873 - 50[\%C]} \right] = \frac{P_{\text{CO}}^2}{P_{\text{CO}_2} \cdot a_{\text{C}}} \quad (2.11)$$

If the oxygen blowing into the converter bath is not pure but contains some inert gases such as nitrogen, argon etc. and the total pressure is assumed to be  $P$ , we would have

$$P_{CO} = P \cdot x_{CO} \quad (2.12)$$

$$P_{CO_2} = P \cdot x_{CO_2} \quad (2.13)$$

$$P_{Inr} = P \cdot x_{Inr} \quad (2.14)$$

Where  $x_{CO}$ ,  $x_{CO_2}$ ,  $x_{Inr}$  represent the mole fractions of CO, CO<sub>2</sub> and inert gas in the decarburization zone, respectively, and

$$x_{CO} + x_{CO_2} + x_{Inr} = 1 \quad (2.15)$$

On the other hand, the activity of carbon can be expressed in terms of the products of [%C] and activity coefficient,  $f_C$  i.e.

$$a_C = [\%C] f_C \quad (2.16)$$

Substituting Eqs (2.12) to (2.16) into Eq (2.11) generate

$$\exp \left[ 15.30 - \frac{16759}{1873 - 50[\%C]} \right] = \frac{P \cdot x_{CO}^2}{(1 - x_{Inr} - x_{CO})[\%C] \cdot f_C} \quad (2.17)$$

Let two other quantities be defined as  $X_{CO}$  and  $X_{CO_2}$  (which are relative contents of CO and CO<sub>2</sub> in CO + CO<sub>2</sub>)

$$X_{CO} = x_{CO} / (x_{CO} + x_{CO_2}) = x_{CO} / (1 - x_{Inr}) \quad (2.18)$$

$$X_{CO_2} = x_{CO_2} / (x_{CO} + x_{CO_2}) = x_{CO_2} / (1 - x_{Inr}) \quad (2.19)$$

Substituting Eqs (2.18) and (2.19) into Eq (2.17) we obtain

$$\exp\left[15.30 - \frac{16759}{1873 - 50[\%C]}\right] = \frac{PX_{CO}^2(1 - x_{in})}{(1 - X_{CO})[\%C] \cdot f_C} \quad (2.20)$$

The above relation gives the dependence of relative content of the carbon monoxide on the carbon concentration in the hot metal during the BOP operation. Based on this solution the relative mole fraction of CO can be calculated if carbon content and  $f_C$  are known.

Bensel et al [4] have used the following expression for  $f_C$ .

$$f_C = \alpha [\% C] \quad (2.21)$$

where,

$$\alpha = 0.167 \quad \text{when} \quad [\% C] > 1\%$$

$$\alpha = 0.2 \quad \text{when} \quad [\% C] < 1\%$$

These are approximation formulae and they completely neglect the effect of temperature on  $f_C$ . Rist and Chipman [5] have given a Equation, which explains the effect of temperature on activity coefficient of carbon

$$\begin{aligned} \log f_C = & 0.1666 [\% C] - 0.01585 [\% C]^2 + 9.9613 \times 10^{-7} [\% C]^3 \quad (T-273) \\ & + 3.0246 \times 10^{-5} [\% C]^4 \quad (T-273) \end{aligned} \quad (2.22)$$

The decarburization rate depends on the oxygen blow rate into the furnace. If the rate of oxygen blow is  $dn_{O_2}/dt$  (mol/ min) and the decarburization rate  $dn_C/dt$ , then from mass balance considerations



$$(1 - x_{\text{Inr}}) \frac{dn_{\text{O}_2}}{dt} = - \frac{dn_{\text{C}}}{dt} \left( X_{\text{CO}_2} + \frac{1}{2} X_{\text{CO}} \right) \quad (2.23)$$

Where the factor  $(1 - X_{\text{Inr}})$  reflects the purity of oxygen. The negative sign stems from the decreasing carbon content during decarburization. It is implicitly assumed that oxidation of other elements like P, Mn, Fe, S is negligible in high carbon regime and this is approximately so.

Expressing in terms of [%C] and the flow rate  $Q_o$  ( $\text{Nm}^3/\text{ton}$ ) the above equation becomes

$$\frac{d[\%C]}{dt} = \frac{-Q_o(1 - x_{\text{Inr}})}{1.87 \times 10^{-5} (1 - 0.5 X_{\text{CO}}) W_t} \quad (2.24)$$

where,

$W_t$  = bath weight in gms

[%C] = weight percent of carbon

When carbon content is less than 0.3, the decarburization will be controlled by mass transfer of carbon in the melt instead of oxygen and it can be expressed as

$$dn_{\text{C}}/dt = -k_d \cdot A \cdot (C^b - C^i) \quad (2.25)$$

where,

$C^b, C^i$  = bulk and interfacial concentration of carbon, mol/cc

$k_d$  = mass transfer coefficient (cm/sec)

$A$  = bath / oxygen interface area ( $\text{cm}^2$ )

Since the reaction between carbon and oxygen at high temperature is very fast,  $C_i$  is negligible (except towards end of the blow) and hence Eq (2.25) can be written as:

$$dn_C / dt = -k_d.A. (C^b) \quad (2.26)$$

$$\text{Or} \quad \frac{d[\%C]}{dt} = \frac{-k_d A}{V} [\%C] \quad (2.27)$$

where,

$V$  = melt volume

## 2.3 Exponential Model

### 2.3.1 Model by Bessho et al.

Bessho et al.[6] have developed a dynamic model, based on exponential dependence of decarburization rate on carbon content . This model has been applied to estimate carbon content and temperature of Q -BOP heats after sublance measurement.

Exponential model is expressed as

$$-\frac{dC}{dO_2} = \xi + \tau \exp(\phi C) \quad (2.28)$$

where ,

$$\tau = -\xi \exp\left[\frac{C_0}{C_p - C_0}\right]$$

$$\text{and } \phi = \frac{-1}{C_p - C_0}$$

Then Eq (2.28) becomes

$$-\frac{dC}{dO_2} = \xi \left[ 1 - \exp\left(\frac{C_0 - C}{C_p - C_0}\right) \right] \quad (2.29)$$

where,

$\xi$  = theoretical maximum decarburization rate

$C_0$  = Critical carbon content below which decarburization does not substantially occur and is found to be 0.01% for Q- BOP.

$C_p$  = a parameter derived statistically based on operational variables.

Value of ' $\xi$ ' can be calculated for a converter with oxygen flow rate  $Q_o = 600$  Nm<sup>3</sup>/min and weight of bath  $Wt = 300$  tons as follows:

$$\xi = \frac{\frac{600}{22.4} \times 12 \times 2}{300 \times 1000} = 0.214\% C / \text{min}$$

By integrating the Equation (2.29)

$$\int \frac{-dC}{\left(1 - \exp\frac{C_0 - C}{C_p - C_0}\right)} = \int \xi dO_2$$

$$\text{Or } \int \frac{1}{1 - e^{\frac{C_0 - C}{C_p - C_0}}} dC = -\xi \Delta O_2$$

$$\text{Let } t = e^{\frac{C_0 - C}{C_p - C_0}}$$

$$\log_e t = \frac{C_0 - C}{C_p - C_0}$$

By differentiating, we get

$$\frac{dt}{t} = \frac{d}{dC} \left[ \frac{C_0}{C_p - C_0} - \frac{C}{C_p - C_0} \right]$$

$$\text{Or } dC = \frac{-(C_p - C_0)}{t} . dt$$

Substituting for dC value, we get

$$-\xi \Delta O_2 = \int \frac{1}{1-t} \cdot \frac{-(C_p - C_0)}{t} . dt$$

$$\text{Or, } \xi \Delta O_2 = (C_p - C_0) \int \left( \frac{1}{1-t} + \frac{1}{t} \right) dt$$

$$= (C_p - C_0) . (-\ln[1-t] + \ln[t])$$

$$= (C_p - C_0) \left[ -\ln \left( 1 - \exp \frac{C_0 - C}{C_p - C_0} \right) + \ln \left( e^{\frac{C_0 - C}{C_p - C_0}} \right) \right]$$

$$= (C_p - C_0) \left[ -\ln \left( 1 - \exp \frac{C_0 - C}{C_p - C_0} \right) + \frac{C_0 - C}{C_p - C_0} \right]$$

Taking the integration in the limits of  $C_{SL}$  to  $C_{fa}$ , we get

$$\xi . \Delta O_2 = (C_p - C_0) \left[ -\ln \left( \frac{1 - \exp \frac{C_0 - C_{fa}}{C_p - C_0}}{1 - \exp \frac{C_0 - C_{SL}}{C_p - C_0}} \right) + \frac{C_0 - C_{fa}}{C_p - C_0} - \frac{C_0 - C_{SL}}{C_p - C_0} \right]$$

Or ,

$$\xi . \Delta O_2 = (C_p - C_0) \left[ -\ln \left( \frac{1 - \exp \frac{C_0 - C_{fa}}{C_p - C_0}}{1 - \exp \frac{C_0 - C_{SL}}{C_p - C_0}} \right) + \frac{C_{SL} - C_{fa}}{C_p - C_0} \right]$$

$$\Delta O_2 = \frac{(C_0 - C_p)}{\xi} \left[ \ln \left( \frac{1 - \exp \frac{C_0 - C_{fa}}{C_p - C_0}}{1 - \exp \frac{C_0 - C_{SL}}{C_p - C_0}} \right) + \frac{C_{fa} - C_{SL}}{C_p - C_0} \right] \quad (2.30)$$

where,

$C_{SL}$  = carbon content determined by sensor lance

$C_{fa}$  = the aimed carbon content

$\Delta O_2$  = the amount of oxygen required (per ton of charge) to reduce the carbon content from  $C_{SL}$  to  $C_{fa}$ .

The carbon content at any arbitrary time after the measurement by the sensor lance can be calculated as follows.

From the Eq(2.32), we can get

$$\frac{\xi \Delta O_2}{C_0 - C_p} - \frac{C_{fa} - C_{SL}}{C_p - C_0} = \left[ \ln \left( \frac{1 - \exp \frac{C_0 - C_{fa}}{C_p - C_0}}{1 - \exp \frac{C_0 - C_{SL}}{C_p - C_0}} \right) \right]$$

$$\text{Or, } \exp \left[ \frac{-\xi \Delta O_2}{C_p - C_0} - \frac{C_{fa} - C_{SL}}{C_p - C_0} \right] = \frac{1 - \exp \left( \frac{C_0 - C_{fa}}{C_p - C_0} \right)}{1 - \exp \left( \frac{C_0 - C_{SL}}{C_p - C_0} \right)}$$

$$\text{Or, } \frac{\exp \left( \frac{-\xi \Delta O_2}{C_p - C_0} \right)}{\exp \left( \frac{C_{fa} - C_{SL}}{C_p - C_0} \right)} = \frac{1 - \exp \left( \frac{C_0 - C_{fa}}{C_p - C_0} \right)}{1 - \exp \left( \frac{C_0 - C_{SL}}{C_p - C_0} \right)}$$

Or,

$$\exp\left(\frac{-\xi.\Delta O_2}{C_p - C_0}\right) - \exp\left(\frac{-\xi.\Delta O_2 + C_0 - C_{SL}}{C_p - C_0}\right) = \exp\left(\frac{C_{fa} - C_{SL}}{C_p - C_0}\right) - \exp\left(\frac{C_0 - C_{fa} + C_{fa} - C_{SL}}{C_p - C_0}\right)$$

Or,

$$\exp\left(\frac{-\xi.\Delta O_2}{C_p - C_0}\right) - \exp\left(\frac{-\xi.\Delta O_2 + C_0 - C_{SL}}{C_p - C_0}\right) + \exp\left(\frac{C_0 - C_{SL}}{C_p - C_0}\right) = \exp\left(\frac{C_{fa} - C_{SL}}{C_p - C_0}\right)$$

Or ,

$$\exp\left(\frac{-\xi.\Delta O_2}{C_p - C_0}\right) - \exp\left(\frac{-\xi.\Delta O_2 + C_0 - C_{SL}}{C_p - C_0}\right) + \exp\left(\frac{C_0 - C_{SL}}{C_p - C_0}\right) = \exp\left(\frac{C_{fa}}{C_p - C_0}\right) \cdot \exp\left(\frac{-C_{SL}}{C_p - C_0}\right)$$

Or,

$$\exp\left(\frac{-\xi.\Delta O_2 + C_{SL}}{C_p - C_0}\right) - \exp\left(\frac{-\xi.\Delta O_2 + C_0 - C_{SL} + C_{SL}}{C_p - C_0}\right) + \exp\left(\frac{C_0 - C_{SL} + C_{SL}}{C_p - C_0}\right) = \exp\left(\frac{C_{fa}}{C_p - C_0}\right)$$

By dividing  $\exp\left(\frac{-\xi.\Delta O_2 + C_{SL}}{C_p - C_0}\right)$  both sides of above equation, we get

$$1 - \exp\left(\frac{C_0 - C_{SL}}{C_p - C_0}\right) + \exp\left(\frac{C_0 - C_{SL} + \xi.\Delta O_2}{C_p - C_0}\right) = \exp\left(\frac{C_{fa}}{C_p - C_0}\right) \cdot \exp\left(\frac{\xi.\Delta O_2 - C_{SL}}{C_p - C_0}\right)$$

Or,

$$\frac{1 \cdot \exp\left(\frac{\xi.\Delta O_2 - C_{SL}}{C_p - C_0}\right)}{1 - \exp\left(\frac{C_0 - C_{SL}}{C_p - C_0}\right) + \exp\left(\frac{C_0 + \xi.\Delta O_2 - C_{SL}}{C_p - C_0}\right)} = \exp\left(\frac{C_{fa}}{C_0 - C_p}\right)$$

Or,

$$C_{fa} = (C_0 - C_p) \cdot \ln \left[ \frac{R}{1 - \exp\left(\frac{C_0 - C_{SL}}{C_p - C_0}\right) + R \cdot \exp\left(\frac{C_0}{C_p - C_0}\right)} \right] \quad (2.31)$$

where

$$R = \exp\left(\frac{\xi.\Delta O_2 - C_{SL}}{C_p - C_0}\right)$$

where  $\Delta O_2$  ( $Nm^3$  /ton of charge ) is the amount of oxygen blown after the measurement by sensor lance. The value of  $C_p$  in the above equations is estimated from multiple linear regression (MLR) analysis which involves the carbon content and temperature of the bath monitored by the sensor lance. The MLR equation to estimate  $C_p$  can be expressed as

$$C_p = a_0 + \sum_{i=1}^m a_i . x_i \quad (2.32)$$

Thus,

$a_0, a_i$  = regression constant and regression coefficients.

$x_i$  = operational variables as shown below

The operational variables used by Bessho et al. For regression analysis are

$x_i$	meaning
1	real carbon content at blowing end
2	real bath temperature at blowing end
3	hot ratio (=wt of bath /wt. of scrap )
4	carbon content by sensor lance
5	bath temperature by sensor lance
6	amount of lime used after one point check by sensor lance.
7	total amount of lime and dolomitic lime used
8	calculated basicity

An attempt has been made in Chapter (3) to apply the above relationship to the present work data (301 heats). It may however be noted that it is not correct to include the operational variables like

$X_1$  = real carbon content at blowing end

$X_2$  = real bath temperature at blowing end

$X_4$  = carbon content by sensor lance

as independent variables in the regression Equation to estimate the dependent variable ' $C_p$ '.

This is because  $X_1$ ,  $X_2$ , are not known a priori at the time of subblance measurement and  $X_4$  is already used in the Eq (2.30) to calculate  $C_p$

Bessho et al. used a semi empirical equation to estimate the temperature rise.

$$T_f = T_{SL} + P.\Delta O_2 + Q\left(\frac{1}{C_f} - \frac{1}{C_{SL}}\right) + R \quad (2.33)$$

where,

$T_f, C_f$  = the temperature and carbon content of the bath at blowing end respectively.

$T_{SL}, C_{SL}$  = the temperature and carbon content of the bath measured by the sensor lance

$\Delta O_2$  = amount of blowing after sensing ( Nm<sup>3</sup>/ton of charge)

P, Q, R = Parameters calculated from multiple regression analysis by using actual operational data such as lance height, slag volume , etc.

### 2.3.2 Model by Byun et al.

Byun et al. [7] employed a simplified form of exponential model Eq. (2.29), as:

$$-W_{st} \frac{d[C]}{dO_2} = \alpha [1 - e^{-\beta(C-C_0)}] \quad (2.34)$$

$W_{st}$  = Weight of molten steel (kg).



Here the term  $\beta$  is same as  $1/(C_p - C_o)$  and  $\alpha$  is same as  $\xi$  in Eq (2.29). It is implied that  $\beta$  represents combined effect of  $C_p$  and  $C_o$  on decarburization.

Integrating Eq (2.34) from subblance carbon content  $C_s$  to aimed carbon  $C_e$  gives the oxygen consumption from the in - blow subblance measurement to the blow end

$$\Delta O_{2,cal} = \int_{O_{2,e}}^{O_{2,s}} dO_2 = - \int_{C_s}^{C_e} \left[ \frac{W_{st}}{1 - e^{-\beta(C-C_o)}} \right] d[C] = \frac{-W_{st}}{\alpha} \int_{C_s}^{C_e} \frac{1}{1 - e^{-\beta(C-C_o)}} d[C] \quad (2.35)$$

$$\text{Let } t = e^{-\beta(C-C_o)}$$

$$\ln(t) = -\beta(C-C_o)$$

By differentiating, we get

$$\frac{dt}{t} = -\beta \cdot (dC)$$

$$dC = \frac{-1}{\beta} \cdot \frac{dt}{t}$$

On substituting dC value

$$\Delta O_{2,cal} = \frac{-W_{st}}{\alpha} \cdot \int_{C_s}^{C_e} \frac{1}{1-t} \cdot \frac{-1}{\beta} \cdot \frac{dt}{t}$$

$$\text{Or,} \quad \Delta O_{2,cal} = \frac{-W_{st}}{\alpha \cdot \beta} \cdot \int_{C_s}^{C_e} \frac{1}{1-t} \cdot \frac{dt}{t}$$

$$= \frac{-W_{st}}{\alpha \cdot \beta} \cdot \int_{C_s}^{C_e} \frac{1}{t} + \frac{1}{1+t} \cdot dt$$

$$= \frac{-W_{st}}{\alpha \cdot \beta} \cdot [\ln(t) - \ln(1-t)] \Big|_{C_s}^{C_e}$$

By substituting t value, we get

$$\begin{aligned}
&= \frac{-W_{st}}{\alpha.\beta} \left[ \ln(e^{-\beta(C-C_0)}) - \ln(1 - e^{-\beta(C-C_0)}) \right] \frac{C_e}{C_s} \\
&= \frac{-W_{st}}{\alpha.\beta} \left[ -\beta(C - C_0) - \ln(1 - e^{-\beta(C-C_0)}) \right] \frac{C_e}{C_s} \\
\text{Or, } \Delta O_{2,cal} &= \frac{W_{st}}{\alpha.\beta} \left[ \beta(C_e - C_s) - \ln \left( \frac{1 - e^{-\beta(C_e - C_s)}}{1 - e^{-\beta(C_s - C_e)}} \right) \right] \quad (2.36)
\end{aligned}$$

The effect of other operational variables on oxygen consumption can be incorporated through multiple linear regression as

$$\Delta O_{2,cal} = \frac{W_{st}}{\alpha.\beta} \left[ \beta(C_e - C_s) - \ln \left( \frac{1 - e^{-\beta(C_e - C_s)}}{1 - e^{-\beta(C_s - C_e)}} \right) + \sum_i \gamma_i (X_i - \ddot{X}_i) + \gamma_0 \right] \quad (2.37)$$

where,

$\gamma_i$  = regression coefficient

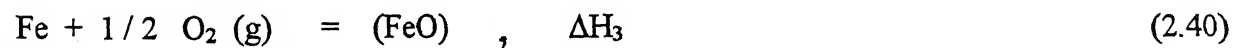
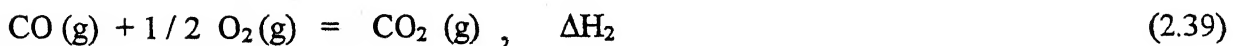
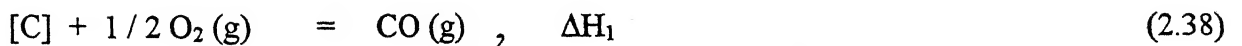
$\gamma_0$  = regression Constant

$X_i$  = operational variables ,

$\ddot{X}_i$  = Standard operational variables

### 2.3.2.1 Temperature calculation model

Temperature at the end of blow can be calculated by considering the heats evolved in various reactions



$$\frac{1}{2} O_2 = [O] , \quad \Delta H_4 \quad (2.41)$$

Where  $\Delta H_i$  is the heat produced from each reaction (Kcal / Nm<sup>3</sup> - O<sub>2</sub>)

Over all heat balance (excluding heat losses) can be written as

$$C_p W_{st} dT = \Delta H_1 dO_c + \Delta H_2 dO_{co} + \Delta H_3 dO_{Fe} + \Delta H_4 dO_{dis} \quad (2.42)$$

where,

$C_p$  = Specific heat capacity of molten steel (Kcal / kg<sup>0</sup> C)

$O_c$  = oxygen combined with carbon to form CO (Nm<sup>3</sup> - O<sub>2</sub>)

$O_{co}$  = oxygen combined with CO to form CO<sub>2</sub> (Nm<sup>3</sup> - O<sub>2</sub>)

$O_{Fe}$  = oxygen combined with Fe to form FeO (Nm<sup>3</sup>-O<sub>2</sub>)

$O_{dis}$  = oxygen dissolved in liquid steel (Nm<sup>3</sup>-O<sub>2</sub>)

In Eq(2.40), the heat of Fe oxidation and the heat produced by oxidation of CO to CO<sub>2</sub> are not greatly different at steel making temperature, i.e.  $\Delta H_2 \approx \Delta H_3$ . In the later stage of BOF blowing process, it is generally accepted that the product of dissolved carbon and oxygen in liquid steel is constant.

$$[C] \times [O] = K'_4 \quad (2.43)$$

Therefore the amount of dissolved oxygen can be expressed as a function of carbon content in steel.

$$dO_{dis} \times \frac{22.4}{32} \frac{W_{st}}{100} = -\frac{22.4}{32} \frac{W_{st}}{100} \frac{K'_4}{[C]^2} d[C] = -\frac{K_4}{[C]^2} d[C] \quad (2.44)$$

Assuming that the carbon removal from steel melt mainly occurs by Eq(2.38), the oxygen consumption for decarburization can be obtained as

$$dO_c = -\frac{11.2}{12} \frac{W_{st}}{100} d[C] = -K_1 d[C] \quad (2.45)$$

If an assumption is made that all lance oxygen is consumed by reactions (2.38) to (2.41),

$$dO_2 = dO_C + dO_{CO} + dO_{dis},$$

the term  $dO_{Fe} + dO_{CO}$  is expressed as follows.

$$dO_{Fe} + dO_{CO} = dO_2 - (dO_C + dO_{dis}) = dO_2 + K_1 d[C] + K_4 d[C]/[C]^2 \quad (2.46)$$

If  $H_i$  are assumed to be independent of temperature, the following differential equation can be obtained from Eq(2.42) through (2.46).

$$dT = (\delta_1 + \delta_2 / [C]^2) d[C] + \delta_3 dO_2 \quad (2.47)$$

where,

$$\delta_1 = (\Delta H_2 - \Delta H_1) K_1 / (C_p \cdot W_{st})$$

$$\delta_2 = (\Delta H_2 - \Delta H_4) K_4 / (C_p \cdot W_{st})$$

$$\delta_3 = \Delta H_2 / (C_p \cdot W_{st})$$

Integration of Eq(2.47) from in blow measurement to the end blow gives a linear function of temperature rise.

$$\begin{aligned} \Delta T_{cal} &= \int_{T_s}^{T_e} dT = \delta_1 \int_{C_s}^{C_e} dC + \delta_2 \int_{C_s}^{C_e} \frac{dC}{[C]^2} + \delta_3 \int_{O_{2,s}}^{O_{2,e}} dO_2 \\ &= \delta_1 (C_s - C_e) + \delta_2 \left( \frac{1}{C_e} - \frac{1}{C_s} \right) + \delta_3 \Delta O_2 \end{aligned} \quad (2.48)$$

Where  $T_s$ ,  $T_e$  are temperature measured at in blow and blow-end and  $O_2$  is total oxygen blow between these measurements.

In order to fit this model better to the actual temperature data, parameters  $\delta_i$  in Eq(2.48) are modified by the multiple regression analysis as discussed in the decarburization model. In the present work operational variables other than the amount of oxygen and carbon content were also included in this model such as the steel temperature at subblance

measurement, slag volume, HMR, lining life, lance height and the amount of iron ore used.

Therefore, the equation for the temperature increase can be rewritten as:

$$\Delta T_{actual} = \varepsilon_1 (C_s - C_e) + \varepsilon_2 \left( \frac{1}{C_e - C_s} \right) + \varepsilon_3 \Delta O_2 + \sum_i \chi_i (Z_i - \ddot{Z}_i) + \chi_0 \quad (2.49)$$

where,

$\chi_i, \varepsilon_i$  = regression coefficients

$\chi_0$  = constant

$Z_i$  = Operational variables

$\ddot{Z}_i$  = Standard operational variables (mean values)

#### 2.3.2.2 Feedback model

There will always be deviation of oxygen quantity and temperature rise for a heat which are not accounted for by the explanatory relationships such as Eq(2.37),(2.48) and thus some part of those deviations will remain unpredictable. In order to minimise the error various steps can be taken. The model can be modified to include the perturbing factor which may be explained by the selected model parameter. The model parameter for upcoming heat can be adjusted by a time series analysis of the posterior calculation of actual turndown data of preceding heats. In other words the new model parameters for upcoming heat can be expressed as a function of old parameter of preceding heats.

One of the most important concerns in developing feedback model is how to select the adapted model parameters. In this work, various model parameters,  $\theta_i$  for

decarburization model and  $\phi_i$  for temperature calculation model were employed and the general form of equations used are

$$\Delta O_2 = \theta_1 \left[ \frac{W_{st}}{\theta_2 \theta_3} \ln \frac{1 - e^{\theta_4 (C_s - C_o)}}{1 - e^{\theta_3 (C_e - C_o)}} + \sum_i \gamma_i (X_i - \ddot{X}_i) + \theta_4 \right] \quad (2.50)$$

$$\Delta T = \phi_1 \left[ \varepsilon_1 (C_s - C_e) + \varepsilon_2 \left( \frac{1}{C_e} - \frac{1}{C_s} \right) + \phi_2 \Delta O_2 + \sum_i \chi_i (Z_i - \ddot{Z}_i) + \phi_3 \right] \quad (2.51)$$

In addition to above, the following time - series forecasting methods can be tested to obtain appropriate feed back model.

#### Method 1 : Single moving average

This technique consists of taking a set of observed values, finding the average of those values, then using that average as the forecast for the next period.

$$F_{t+1} = (X_t + X_{t-1} + \text{-----} + X_{t-N+1}) / N \quad (2.52)$$

where,

$F_{t+1}$  = the forecast value for the next period

$X_t$  = the most recent observation

$N$  = the number of historical data.

#### Method 2 : Exponential smoothing method.

This forecasting is based on weighting the most recent observation with a weight of value,  $K^*$  whose value is between 0 and 1 and weighting the most recent forecast with a weight of value,  $(1 - K^*)$ .

$$F_{t+1} = K^* X_t + (1 - K^*) F_t \quad (2.53)$$

where,

$K^*$  = Smoothing factor

### Method 3 : ARMA method

In this model, the series to be forecast is expressed as a function of both previous values of the series ( anti regressive term ) and previous error values from forecasting ( moving average term ) . ARMA (2, 1) model used in Byun et al. model was

$$F_{t+1} = \lambda_1 X_t + \lambda_2 X_{t-1} - \mu_1 e_t \quad (2.54)$$

where,

$\lambda_i, \mu_1$  = coefficients.

$e_t$  = the most recent error from forecasting .

Of the above three methods, the exponential smoothing method has been reported to give the best result with a  $K^*$  value of 0.1.

The procedure for On-line application of the model is as follows:

The in- blow subblance measurement is made when 80% of total oxygen amount, presumed by the static model has been blown. At this point, the decarburization model starts a calculation of the oxygen amount to be blown for the aimed carbon content. The temperature increment in this dynamic period is then calculated based on the amount of oxygen to be blown. If the calculated end- point temperature is higher than the aimed one, the amount of coolant to be added is determined. If the calculated temperature is lower than the aimed one, the heat has to be over blown. The bath temperature and the carbon content in steel at turndown are used for adapting the model parameters for the next heat.

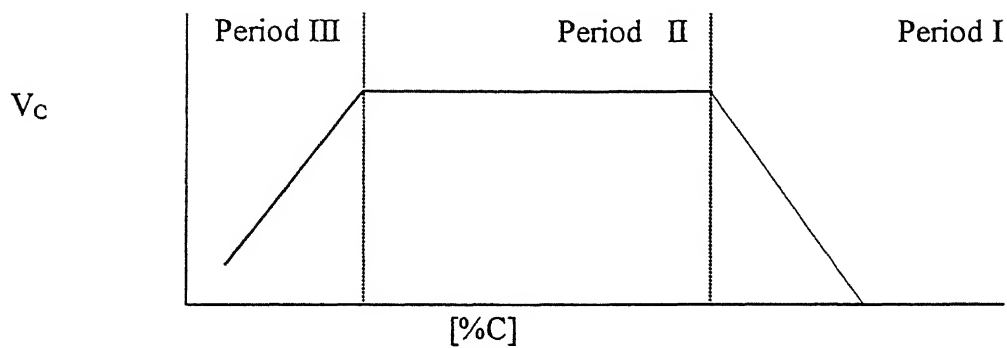
## 2.4 Model by Szegedi et al.

Szegedi et al [8] have developed a model for the adjustment of carbon content of steel by dividing the decarburization process into 3 periods, namely

I . Thermodynamic period

II . Reaction kinetic period

III . Chemical period



where,

$$V_c = \frac{-d[\%C]}{dt}$$

The formulae to calculate the decarburization rate and time taken for the blow for each period are as follows.

The decarburization rate for the period I is obtained on the basis of operational data as

$$V_{C,I} = 0.1071.i. [-0.1421.C_B - 0.7366.Si_B - 0.0425.i + 1.4987] \quad (2.55)$$

where,

$$V_{C,I} = \text{rate of carbon oxidation}(\%C/\text{min})$$



$i$  = intensity of blowing ( $\text{m}^3 \text{O}_2/\text{t steel.min}$ )

$C_B$  = carbon content of charge (%)

$\text{Si}_B$  = silicon content of charge (%)

Time taken for computing the period I is given by

$$t_I = 100 \cdot \text{Si}_B [i.(2.031 \cdot C_B + 7 \cdot \text{Si}_B + 0.106 \cdot i - 6)] \text{min} \quad (2.56)$$

Similarly for the reaction kinetic period II

$$V_{C,II} = 0.1071 \cdot i \quad (2.57)$$

and time necessary for second period is

$$t_{II} = 9.375 (C_B - 0.046) / (-1.942 - \text{Si} \cdot A / (i \cdot B)) \quad (2.58)$$

where,

$$A = C_B + 5.1728 \cdot \text{Si}_B + 0.2981 \cdot i - 10.52426$$

$$B = 0.4217 - 0.1426 \cdot C_B - 0.4918 \cdot \text{Si}_B - 0.00744 \cdot i$$

The third period is chemical period for which the rate of carbon oxidation is

$$V_{C,III} = 12.89 [\%C] \cdot \exp (-6590.73/T) \quad (2.59)$$

The regression analysis of operational data has shown that

$$t_{III} = \frac{\exp \frac{7323}{21422 - [\%C]}}{1289} \cdot \ln \frac{0.208 \cdot i + 0.046}{[\%C]}, \text{min} \quad (2.60)$$

The activation energy of the reaction is

$$G^T = -R.6590.73 \text{ J/ mole.} \quad (2.61)$$

Total time for blowing  $t = t_I + t_{II} + t_{III}$

By equating the decarburization rates periods II and III (i.e.  $VC_{II} = VC_{III}$ ) they have derived a formula to calculate the critical carbon constant  $[C_k]$ .

$$C_k = 0.208.(i) + 0.046 . \quad (2.62)$$

They have experimented this model in the range of 0.01 -4.0 C wt % .and have shown that the adjustment and the more exact control of carbon content ensure a significant saving of time and material costs.

## 2.5 Models Based on Exhaust Gas Composition

### 2.5.1 Model by Fukumi et al

Fukumi et al [9] have developed a refining control model based on exhaust gas information measured by mass spectrometer. This model consists of calculation models that use substance information to estimate various values as follows.

- Calculation and estimation of the oxidation degree ( $WO_2$ )
- Estimation of (T.Fe)
- Estimation of decarburization

- Estimation of temperature in steel
- Estimation of oxygen content in steel.

#### 2.5.1.1 Calculation and estimation of oxidation degree ( $WO_2$ )

$WO_2$  is defined as Eq(2.63) based on oxygen balance calculated by refining conditions (top and bottom gas flow rate, amount of flux, etc.) and exhaust gas information (analysis, flow rate)

$$WO_2 = [ \int (f_i(Q,F) - f_o(V,A))dt ] / WM \quad (2.63)$$

where,

$f_i$  = input oxygen

$f_o$  = output oxygen

$WO_2$  = oxidation degree

$Q$  = top blow oxygen

$F$  = amount of coolant

$V$  =  $O_2, CO, CO_2$  volume in exhaust gas

$A$  = sucked air or slopping gas volume.

$WO_2$  indicates oxygen in slag and steel, and this value is the most important parameter in this model. The volume of air sucked from the converter mouth and slopping gas volume are evaluated with reference to bottom blowing gas, balance of air, Ar and  $N_2$ . Analysed values of exhaust gas have a time lag behind the actual reactions because of gas transport time. At the final stage of blowing when  $WO_2$  is rapidly increased, this time lag must not be neglected. Thus, reacted volume can be calculated at real time by the estimation of  $WO_2$  from Eq(2.64) which is calculated from actual data.

$$dWO_2/dO_2 = \alpha \{1 - \exp [WO_2/\beta]\} \quad (2.64)$$

where,

$WO_2$  = Oxidation

$O_2$  = Input oxygen

$\alpha$  = Constant

$\beta$  = Parameter

### 2.5.1.2 Estimation of total iron

Since  $WO_2$  indicates oxygen in slag and steel,  $WO_2$  has a close relationship with total iron (T.Fe) in slag. In other words, the change of (T.Fe) can be known from the change of  $WO_2$ . Therefore, from (T.Fe) at the first subblance and the increasing amount of  $WO_2$  after the first subblance, the value of (T. Fe) at the final stage can be estimated in real time with reference to Eq. (2.65) - (2.67)

$$(T. Fe)_s = f(QB, FO_2, Cs) \quad (2.65)$$

$$Ws(t) = \alpha WO_2(t) + W_{so} / \{1 - \beta (T. Fe)_s / 100\} \quad (2.66)$$

$$(T.Fe)(t) = (T. Fe)_s + \gamma WO_2(t) / Ws \sim t \quad (2.67)$$

where,

$(T.Fe)_s$  = (T. Fe) at in - blow subblance

$QB$  = bottom blowing gas flow rate

$Cs$  = [C] in steel at in - blow subblance

$WO_2$  = Oxidation degree

$W_{so}$  = Slag volume except (FeO), (MnO), (P<sub>2</sub>O<sub>5</sub>)

$W_s$  = Slag volume

$t$  = time

$\alpha, \beta, \gamma$  = Parameter

### 2.5.1.3 Estimation and prediction of the amount of decarburization

The amount of decarburization utilised for the estimation of steel temperature and prediction of slopping is calculated by Eq (2.68) based on carbon balance from refining conditions and exhaust gas information.

$$\Delta C = [ \int \int f (h_o(V \cdot A) - h_i(F)dt] / WM \quad (2.68)$$

where,

$h_o$  = Output carbon

$h_i$  = Input carbon

$\Delta C$  = Amount of decarburization

$V$  =  $CO, CO_2$  volume in exhaust gas

$A$  = Sucked air volume or slopping gas volume

$F$  = Amount of coolant and flux

At the final stage of blowing , the estimation of decarburization , amount that contains time lag is calculated according to the efficiency of oxygen for decarburization.

#### 2.5.1.4 Estimation of steel temperature

The heating of the steel at the final stage of blowing has a close relationship with the generated amount of (T.Fe); namely the increased amount of  $WO_2$  and amount of decarburization.

Therefore, heating after subblance is estimated by Eq. (2.69).

$$dT/dO_2 = \alpha \cdot dWO_2 / dO_2 - \beta \cdot dC / dO_2 - \gamma W_s WM + \delta \quad (2.69)$$

where,

$T$  = Temperature in steel

$O_2$  = Input oxygen (gas + coolant)

$WO_2$  = Oxidation degree

$C$  = Carbon content in steel

$W_s$  = Slag volume except (FeO) , (MnO) , ( $P_2O_5$ )

$WM$  = Weight of steel

$\alpha, \beta, \gamma, \delta$  = Parameter

#### 2.51.5 Estimation of dissolved oxygen content in steel

Oxygen content in steel is estimated from the oxygen balance Eq (2.70) calculated from (T.Fe) which is evaluated from exhaust gas information and the steel temperature.

$$\log \{[O]\} = \log \{ \alpha (T. Fe) \} + b/T + \gamma \quad (2.70)$$

where,

[O] = Oxygen in steel

T = Temperature in steel

$\alpha, \beta, \gamma$  = Parameter.

### 2.5.2 Model by Iwamura et al

Iwamura et al.[10] have developed a new endpoint control system of BOF with an auto-tuning function for the model parameter based on the measured exhaust gas composition. This system can accurately estimate the steel temperature and the carbon content at the blow-end through one campaign without changing of the model parameter. The dynamic control model consists of an oxygen balance equation and heat balance equation. The amount of oxygen required in a heat is expressed by the sum of the amount of oxygen based on the change of carbon.

$$\frac{F_{O_2} + \eta \sum W_{sub} \cdot O_2}{W_{ST}} = a_0 (C_{SL} - C_{EP}) + a_1 \ln \frac{C_{SL}}{C_{EP}} + a_2 + \sum l_i (X_i - \bar{X}_i) + FB_c \quad (2.71)$$

where,

$a_0, a_1$  = coefficient of oxygen balance

$C_{SL}, C_{EP}$  = carbon contents at subblance measurement and endpoint

$F_{O_2}$  = the amount of oxygen after subblance measurement

$\eta$  = coefficient of oxygen in fluxes

$W_{sub}$  = amount of flux

$O_2$  = the amount of oxygen fluxes

$W_{ST}$  = weight of molten steel

$X_i$  = factor i of operating condition

$\ddot{X}_i$  = mean value of  $X_i$

$l_i$  = coefficient of statistical model

$FB_C$  = adjustment of oxygen balance from the feedback

In the heat balance model, the fundamental equation has been changed from the carbon content to the oxygen basis . In situations where the carbon content of the metal at the endpoint has little variation, temperature variation has stronger relation with the amount of oxygen than the change of carbon content. The heat balance is represented by the following equation.

$$T_{EP} - T_{SL} = b_0 \frac{Fo_2 + \eta \sum W_{sub} \cdot o_2}{W_{ST}} + b_2 + \gamma \sum W_{sub} T_{sub} + \sum l_i (X_i - \ddot{X}_i) + FB_T \quad (2.72)$$

where,

$T_{SL}, T_{EP}$  = temperature at subalance measurement and at the endpoint .

$b_0, b_2$  = coefficient of heat balance .

$\gamma$  = coefficient of cooling capacity

$l_i$  = coefficient of statistical model

$T_{sub}$  = cooling capacity of fluxes

$FB_T$  = adjustment of heat balance from the feedback

### 2.5.2.1 Auto-Parameter -Tuning function



Usually the decarburization efficiency is changed during blowing for each heat. This fact shows that in the oxygen balance equation with a fixed parameter it is difficult to obtain a highly accurate estimate of steel carbon content and temperature at endpoint through one campaign. To solve this problem, Iwamura et al. have added an auto-parameter-tuning function of parameters in oxygen balance Eq.(2.71) using exhaust gas information from a mass spectrometer. The parameters of  $a_0$  and  $a_i$  are adjusted according to the following Equations.

First of all, Eq(2.73) is altered to the following Equation .

$$-W_{st} \cdot \frac{dC}{do_2} = \frac{1}{(a_0 + \frac{a_i}{c})} \quad (2.73)$$

The decarburization efficiency is expressed with the parameter of  $a_0$  and  $a_i$  and the estimated steel carbon content. On the other hand, the actual decarburization efficiency is calculated by

$$\alpha = G \cdot \frac{W_{st} \cdot \Delta C_i}{\Delta o_i} \quad (2.74)$$

where ,

$G$  = gain

$\alpha$  = decarburization efficiency

$i$  = sampling number from substance measuring time to blow-end .

$\Delta C_i$  is the change of steel carbon content and  $\Delta O_i$  is the amount of oxygen during the sampling period  $\Delta t$  as shown below. .

$$\Delta C_i = C_i - C_{i-1} \quad (2.75)$$

$$\Delta O_i = \int_{t'}^{t'+\Delta t} F_{O_2}(\tau) d\tau \quad (2.76)$$

The amount of decarburization in the exhaust gas during  $\Delta t$  is calculated from the following expression using the exhaust gas information.

$$\Delta W_{C,i} = \int_{t'}^{t'+\Delta t} \frac{\{CO(\tau) + CO_2(\tau)\} \cdot Q(\tau) \cdot 12}{3600 \cdot 22.4 \cdot 1000} d\tau \quad (2.77)$$

From Eq. (2.74) and (2.77) we can obtain

$$\alpha_i = G \cdot \frac{\Delta W_{C,i}}{\Delta O_i} \cdot 100 \quad (2.78)$$

when  $C$  is infinity, the term of  $1/C$  in the Eq.(2.73) can be neglected and the parameter of  $a_0$  is expressed from Eq.(2.73) and (2.74) can be shown as

$$a_0 = \frac{1}{\alpha_i} \quad (2.79)$$

In on-line operation, the parameter of  $a_0$  is decided by the average of the actual decarburization efficiency during the maximum decarburization period before substance measuring time as shown in the following equation

$$\alpha_0 = \frac{1}{\sum \alpha_{\max,i} / m} \quad (2.80)$$

where ,

$\alpha_{\max}$  = decarburization efficiency in maximum decarburization period

$m$  = constant of sampling number

On real time after sublance measurement, the parameter of  $a_1$  in Eq.(2.73) is calculated as.

$$a_1 = \frac{(1 - \alpha_0 - \alpha_i)}{\alpha_i} C \quad (2.81)$$

The parameter of  $a_1$  changes in proportion to the decrease of the decarburization efficiency and this function can accurately estimate the steel carbon content.

#### 2.5.2.2 Feedback calculation model

The feed back calculation model has been developed in order to adjust the errors in the dynamic control model. The amount of feedback is calculated by considering the trend in the errors of the dynamic control model in past some heats measured by sublance at blowing and endpoint. The rule of feedback is classified with three cases by the trend of the error as shown below.

Case	The trend of the error of the model	Th amount of feedback
1	$Mdlerro(i-1).Mdlerro(i) \geq 0$	$FB(i) = FB(i-1) + G_{FB}(erro(i) + erro(i-1))/2$
2	$Mdlerro(i-1).Mdlerro(i) < 0$ and $ erro(i)  -  erro(i-1)  > H$	$FB(i) = FB(i-1) + G_{FB}.erro(i)$
3	$Mdlerro(i-1).Mdlerro(i) < 0$ and $ erro(i)  -  erro(i-1)  \leq H$	$FB(i) = FB(i-1)$

where,

$FB(i)$  = feedback value

$Mdlerro(i)$  = error of the model

$erro(i)$  = error of the feedback model

$G_{FB}$  = feedback gain

$H$  = on-detective value

In the oxygen balance equation, the feedback value is adjusted according to the condition of the substance measured carbon content at end point in addition to the above rule of the feedback. This is because the sensitivity of the carbon content for the amount of oxygen varies with the substance measured carbon content in the blowing.

The relationship between carbon content and amount of oxygen can be defined in the following equation

$$C_{EP} = s_1 \cdot \log\left(\frac{\Delta O_2}{W_{ST}}\right) + s_2 \quad (2.82)$$

where,

$s_1, s_2$  = coefficient

The sensitivity of the carbon content to the amount of oxygen is related to the following equation.

$$\varepsilon = \frac{d\Delta o_2}{dC_{EP}} = \frac{1}{s_1} \cdot e^{\left(\frac{C_{EP} - s_2}{s_2}\right)} \quad (2.83)$$

where,

$\varepsilon$  = the sensitivity

The actual feedback value is adjusted with the sensitivity as shown in the following equation.

$$FB'(i) = h \cdot FB(i) \quad (2.84)$$

where,

$$h = \frac{\varepsilon'}{\varepsilon_{base}}$$

where, 
$$\varepsilon' = \frac{d\Delta o_2}{dC_{EP}} = \frac{1}{s_1} \cdot e^{\frac{C_{sim} - s_2}{s_2}}$$

# **CHAPTER 3**

## **EVALUATION OF SUBLANCE MODELS FOR END POINT CARBON AND TEMPERATURE**

### **3.0 Introduction**

Various models for end point control of carbon and temperature have already been discussed in Chapter 2. Operational data for 300 tons and 210 ton converters used in the present work are described in section 3.1. Results obtained for some of these models are presented in section 3.2. So as to verify their applicability to different converters and then find out the best model for a given situation. Comparative performance of different models is discussed in section 3.3.

### **3.1 Operational Data**

The data collected from 4 plants is analyzed in this work . The first set comprises of 301 heats made in a 300 ton converter using an oxygen flow rate of 600 m<sup>3</sup>/min. In plant data set 1 (see Appendix 1) the variables included are : hot metal weight (tons), scrap (tons), hot metal silicon (milli % ), oxygen blown in second blow (O<sub>22</sub>), temperature at sublance measurement (T<sub>SL</sub> in Kelvin), carbon at sublance measurement (C<sub>SL</sub> in milli percent), end point temperature (T<sub>f</sub> in Kelvin), end point carbon (C<sub>f</sub> in milli percent), lime

added in first and second blow (kg), return slag in first and second blow (kg), dolomite added in first and second blow (kg), ore added as a coolant (kg), dolomite special added (kg), lance height (m) and lance life (m).

The plant 2 data of two different converters (but of same capacity) comprises of 1744 heats. The variables included in plant 2 data set (see Appendix 2) are hot metal weight (kg), silicon in hot metal (in milli % ), lime added in first blow (kg), carbon and sublimance measurement ( $C_{SL}$  in milli % ), end point carbon ( $C_f$  in milli % ), temperature at sublimance measurement ( $T_{SL}$  in Kelvin ), end point temperature ( $T_f$  in Kelvin), oxygen blown in second blow ( $m^3$ ), ore added as a coolant (kg). The plant data set 3 (see Appendix 3 ), comprises of 748 heats of a partial campaign of 315 ton converter in which oxygen blowing rate was 900  $m^3/min$ . The variables included in set 3 are hot metal weight (kg), silicon in hot metal (in milli % ), lime added in first blow (kg), carbon at sublimance measurement ( $C_{SL}$  in milli % ), end point carbon ( $C_f$  in milli % ), temperature at sublimance measurement ( $T_{SL}$  in Kelvin ), end point temperature ( $T_f$  in Kelvin), oxygen blown in second blow ( $m^3$ ), ore added as a coolant (kg).

The fourth set, plant 4 data set, (see Appendix 4), comprises of 2235 heats of a 210 ton converter, in which oxygen flow rate is 600  $m^3/min$ . The variables included in plant 4 data are : hot metal weight (kg), silicon in hot metal (in milli % ), lime added in first blow (kg), carbon at sublimance measurement ( $C_{SL}$  in milli % ), end point carbon ( $C_f$  in milli % ), temperature at sublimance measurement ( $T_{SL}$  in Kelvin ), end point temperature ( $T_f$  in Kelvin), oxygen blown in second blow ( $m^3$ ), ore added as a coolant (kg).

Some special features of different sets of data are as follows. Set 1 includes additional data on lance life and lance height. Set 2 comprises of a large number of heats thus making it possible to test the models over a full campaign. Set 3 is for a converter in which very high flow rate of oxygen (900 m<sup>3</sup>/min ) is used and Set 4 is for a converter in which bottom stirring was absent.

## 3.2 Results

### 3.2.1 Application of the Model by Chou et al.

According to Chou et al.[2], the decarburization rate equation as given in chapter 2, (Eq (2.24)) is

$$\frac{d[\%C]}{dt} = \frac{-Q_o(1-x_{lr})}{1.87 \times 10^{-5}(1-0.5X_{CO})W_t}$$

A sample calculation can be done for a converter with

Oxygen flow rate =  $Q_o = 900 \text{ Nm}^3/\text{min}$

Weight of bath =  $W_t = 300 \text{ tons} = 300 \times 10^6 \text{ gm}$

Relative component of CO in (CO+CO<sub>2</sub>) =  $X_{CO} = 0.9947$  at  $[\%C] = 0.3$

On integrating Eq (2.24) in the limit 4 % C to 0.3 %C, we get

$$[\%C]_4^{0.3} = \frac{-Q_o(1-x_{lr})}{1.87 \times 10^{-5}(1-0.5X_{CO})W_t} \cdot t \quad (3.1)$$



Assume the gas used is pure i.e.,  $x_{\text{Inr}} = 0$ , then

$$(0.3 - 4) = \frac{-900(1)}{1.87 \times 10^{-5} (1 - 0.5 \times 0.9947) \times 300 \times 10^6} t$$

Time required to reduced carbon content from 4% to 0.3% becomes

$$t = 11.59 \text{ min.}$$

Equation(2.27) can be written as

$$\frac{-d[\%C]}{dt} = \frac{-k_d \cdot A}{V} \cdot [\%C]$$

On integrating the above equation in the limit of 0.3 to 0.04 %C, we get

$$0.04 = 0.3 \exp (-k_d \cdot A/V \cdot (t - 11.593)) \quad (3.2)$$

Time required for reducing carbon content from 0.3% to 0.04% can now be calculated from the above Eq (3.2), provided  $k_d \cdot (A/V)$  is known.

From Eq (2.24) at  $[\%C] = 0.3$

$$\frac{d[\%C]}{dt} = \frac{-900}{1.87 \times 10^{-5} (1 - 0.5 \times 0.9947) \times 300 \times 10^6}$$

$$\frac{d[\%C]}{dt} = -0.3192$$

Substituting in Eq. (2.27)

$$-0.2128 = \frac{-k_d A}{V} [0.3]$$

$$\text{Or } k_d (A/V) = 1.064$$

Substituting this value in Eq (3.2)

$$\frac{d[\%C]}{dt} = -1.064 [\%C]$$

On integrating the above equation in the limit of 0.3 to 0.04 %C, we get

$$[\%C] = 0.3 \exp (-1.064 (t - 11.593))$$

$$\text{Or } (t - 11.593) = 1.89 \text{ min} = 113.62 \text{ sec}$$

The total blowing time for second and third stages of blow (25% to 100%) is thus

$$t = 11.593 + 1.89$$

$$\text{Or } t = 13.48 \text{ min}$$

In the first stage of blow (approximately 3 minutes ), primarily silicon is oxidized.

Total blowing time is thus  $13.48+3 = 16 \text{ min}$ .

This is approximately same as observed in an actual converter. It proves that the model developed by Chou et al. can be tuned to specific operating conditions in a given converter to predict end point carbon content in an actual converter. The model developed in

present work (as discussed in Section 3.3) is actually an improvement over the model of Chou et al.

### 3.2.2 Application of Exponential Model

As explained in Chapter (2), the decarburization rate is given by Eq (2.29) as

$$\frac{-dC}{dO_2} = \xi \left[ 1 - \exp \frac{C_o - C}{C_p - C_o} \right]$$

where 'C<sub>p</sub>' is dependent upon operational variables.

After several preliminary evaluations, the operational variables chosen for the regression in this work are

- X<sub>1</sub> = hot ratio (wt. of bath/wt. of scrap)
- X<sub>2</sub> = bath temperature by sensor lance (°K)
- X<sub>3</sub> = slag volume (m<sup>3</sup>)
- X<sub>4</sub> = second blow addition (kg)
- X<sub>5</sub> = ore added during end blow as coolant (kg)
- X<sub>6</sub> = lance life (m)
- X<sub>7</sub> = lance height (m)

In Model No.(1) operational variables X<sub>1</sub> to X<sub>5</sub> are considered. In Model No.(2) operational variables X<sub>1</sub> to X<sub>6</sub> are considered. Lance height (X<sub>7</sub>) is used in submodel described later.

#### **Model No. 1 :**

By using stepwise regression, which selects only the significant variables significant in affecting the dependent variable ' $C_p$ ', only  $X_1$  and  $X_5$  were selected in the regression. It is, therefore, assumed that for the operational data chosen only these two variables are affecting the dependent variable ( $C_p$ ).

The value of  $C_p$  can be calculated from the Eq. (2.30) and the end point carbon can be calculated from Eq. (2.31). A sample calculation for one heat is shown below.

### Sample Calculation

**Step 1 :** From the plant data ' $C_p$ ' is calculated by solving the non-linear Eq. (2.30) by iterative process.

$$\Delta O_2 = \frac{(C_o - C_p)}{\xi} \left[ \ln \frac{1 - \exp \frac{C_o - C_{fa}}{C_p - C_o}}{1 - \exp \frac{C_o - C_{SL}}{C_p - C_o}} + \frac{C_{oa} - C_{fSL}}{C_p - C_o} \right]$$

here  $\xi = 0.214$  for  $\Delta O_2 = 4.877172$ ,  $C_o = 10$ ,  $C_{fa} = 61$ ,  $C_{SL} = 257$

$C_p$  value is found out to be = 0.6069

**Step 2 :** With this ' $C_p$ ' and the operational variables calculated from the plant data, regression is done according to the Eq. (2.32)

$$C_p = a_o + \sum_{i=1}^n a_i x_i$$

For these two selected variables, the regression coefficients are found to be

$X_1 = \text{hot ratio} = 6.0$  ;  $a_1 = 0.0187208$

$$X_5 = \text{ore added} = 1004 ; a_5 = -0.0000532$$

$$\text{Regression constant} = a_0 = 0.484089$$

**Step 3 :**  $C_p$  is calculated from Eq. (2.32) by substituting regression coefficients

$$\begin{aligned} \text{i.e. } C_p &= (0.484049) + (0.0187208)(6.0) + (-0.0000532)(1004) \\ &= 0.543001 \end{aligned}$$

**Step 4 :** Now,  $C_p$  is substituted in Eq. (2.31) to estimate the end point carbon.

$$C_{fa} = (C_o - C_p) \frac{R}{1 - \exp \frac{C_o - C_{SL}}{C_p - C_o} + R \exp \frac{C_o}{C_p - C_o}}$$

where,

$$R = \exp \left( \frac{\xi \Delta O'_2 - C_{SL}}{C_p - C_o} \right) \quad (2.35)$$

For

$$C_o = 10$$

$$C_p = 0.543001$$

$$C_{SL} = 257$$

$$\Delta O'_2 = 4.877172$$

$C_{fa}$  is found out to be 54.2 milli percent. Actual end point carbon content for this heat is 61 milli percent.

As explained in the sample calculation, the end point carbon is estimated for all the heats. The plot of actual end point carbon values versus estimated end point carbon values (from the plant data) is shown in Fig.(2) .

The results of this regression for actual versus estimated end point carbon values are as follows (also summarized in Table (1) ).

For the regression curve	Before $\pm 2 \sigma$	After $\pm 2 \sigma$
$y = mx$	$n = 301$ $m = 0.9833$ $\sigma = 14.002$ $R = 0.6612$ $F = 6885$	$n = 284$ $m = 1.00528$ $\sigma = 11.4872$ $R = 0.73016$ $F = 9404$
$y = mx + C$	$n = 301$ $m = 0.5981$ $C = 27.3968$ $\sigma = 12.041$ $R = 0.6612$ $F = 232$	$n = 285$ $m = 0.5958$ $C = 27.002$ $\sigma = 10.1623$ $R = 0.71$ $F = 287$

In Model No. 1 the variable slag volume was replaced with basicity to test whether basicity has an effect on  $C_p$  or not. But again the same variables  $X_1$  (hot ratio) and  $X_5$  (ore added during end blow as coolant) are selected.

### Model No. 2 :

Lance life is taken as additional variable to estimate  $C_p$ . Dependent and independent variables tried are as follows:

Dependent variable in the regression	Independent variables considered for the regression	Selected variables by stepwise regression and their corresponding coefficients
$C_p$	$X_1$ = Lance life $X_2$ = Temperature at subblance $X_3$ = Second blow additions $X_4$ = Slag volume $X_5$ = Ore added during end blow $X_6$ = Hot ratio	$X_1$ = lance life ( $a_1 = -0.0002785$ ) $X_5$ = ore added ( $a_5 = -0.0000572$ ) $X_6$ = Hot ratio ( $a_6 = 0.01855860$ ) Regression constant ( $a_0 = 0.509299$ )

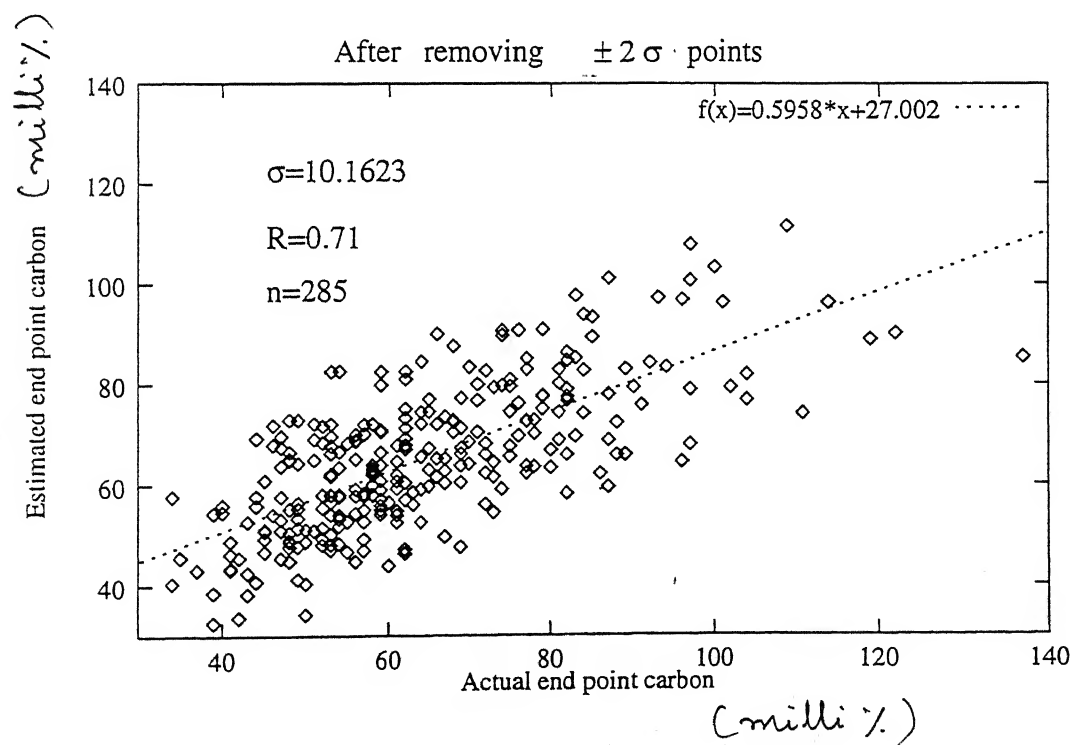
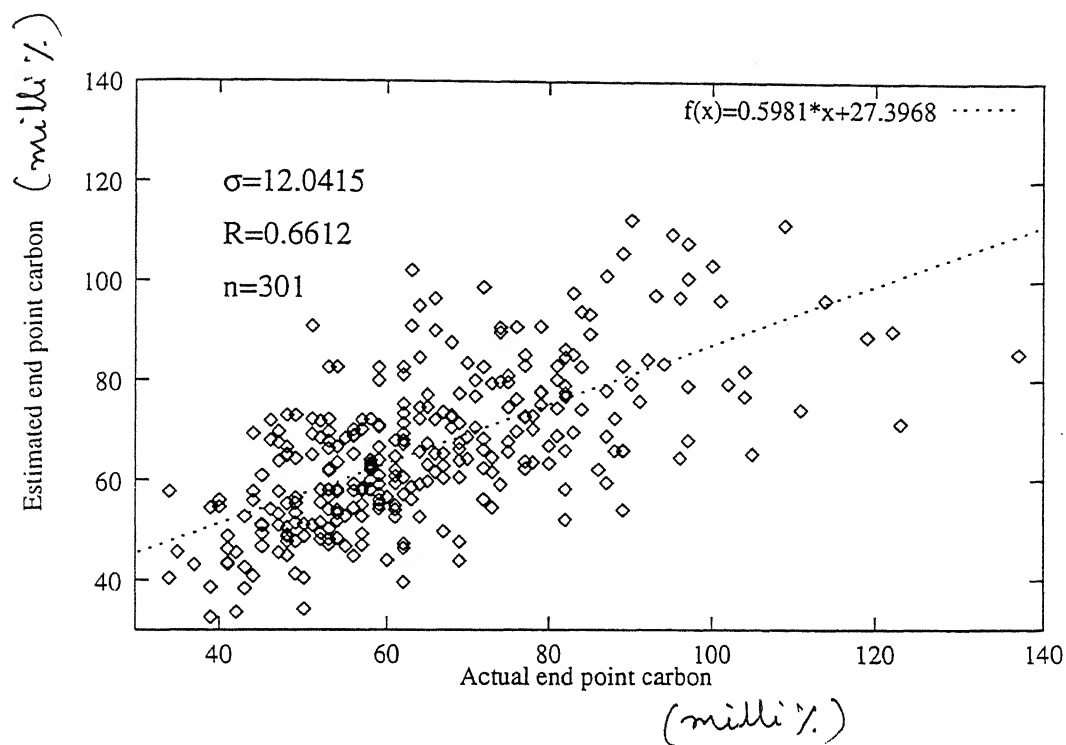


Fig. 2 Actual end point carbon versus Estimated end point carbon for Model No.(1)

With the above selected variables,  $C_p$  is calculated by substituting the coefficients in Eq (2.32), as follows.

$$C_p = 0.509299 - 0.0002785(30) - 0.0000572(1004) + 0.01855860(6.0) \\ = 0.55487$$

The  $C_p$  values are substituted in Eq (2.35) to estimate end point carbon as explained earlier. The results of regression are as follows (also summarized in Table No. ( 1 ) )

For the regression curve	Before $\pm 2 \sigma$	After $\pm 2 \sigma$
$Y = mx$	$n = 301$ $m = 0.98808$ $\sigma = 13.7495$ $R = 0.66998$ $F = 7102$	$n = 292$ $m = 0.9913$ $\sigma = 12.1226$ $R = 0.71026$ $F = 8724$
$Y = mx + C$	$n = 301$ $m = 0.5782$ $C = 27.3066$ $\sigma = 11.7602$ $R = 0.67$ $F = 243$	$n = 287$ $m = 0.5809$ $C = 28.0326$ $\sigma = 9.9284$ $R = 0.7081$ $F = 286$

The standard deviation ( $\sigma$ ) in estimating end point carbon is 9.9284 milli percent. This estimation is better than the earlier one (Model No. 1) i.e. without the lance life for which  $\sigma$  obtained is 10.1623.

### Model No. 3 :

An attempt has been made to reduce the standard deviation in estimating the end point carbon by incorporating mean values of operational variables in MLR equation(2.32). Thus the MLR equation is modified as

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$$C_p = a + \sum_{i=1}^n a_i (X_i - \bar{X}_i) \quad (3.3)$$

$\bar{X}_i$  = mean value of operational variable  $X_i$

According to the above equation,  $C_p$  is calculated and then substituted in Eq (2.35) to estimate the end point carbon.

Dependent variable in the regression	Selected variables by stepwise regression and their corresponding coefficients
$C_p$	$X_1$ = ore added-mean of ore added ( $a_1 = -0.0000532$ ) $X_2$ = (hot ratio-mean of hotratio) ( $a_2 = 0.0187208$ ) Regression constant ( $a_0 = 0.5556$ )

With these selected variables  $C_p$  value is calculated by substituting the coefficients in MLR Eq (3.3) as follows.

$$\begin{aligned}
C_p &= 0.5556 - 0.0000532(409.475) + 0.0187208(0.489400) \\
&= 0.54297
\end{aligned}$$

These  $C_p$  values are substituted in Eq (2.35) to estimate the end point carbon values. The regression between estimated end point carbon and actual end point carbon has been done. The plot of actual end point carbon versus estimated end point carbon has been shown in Fig (3). The details are as follows.

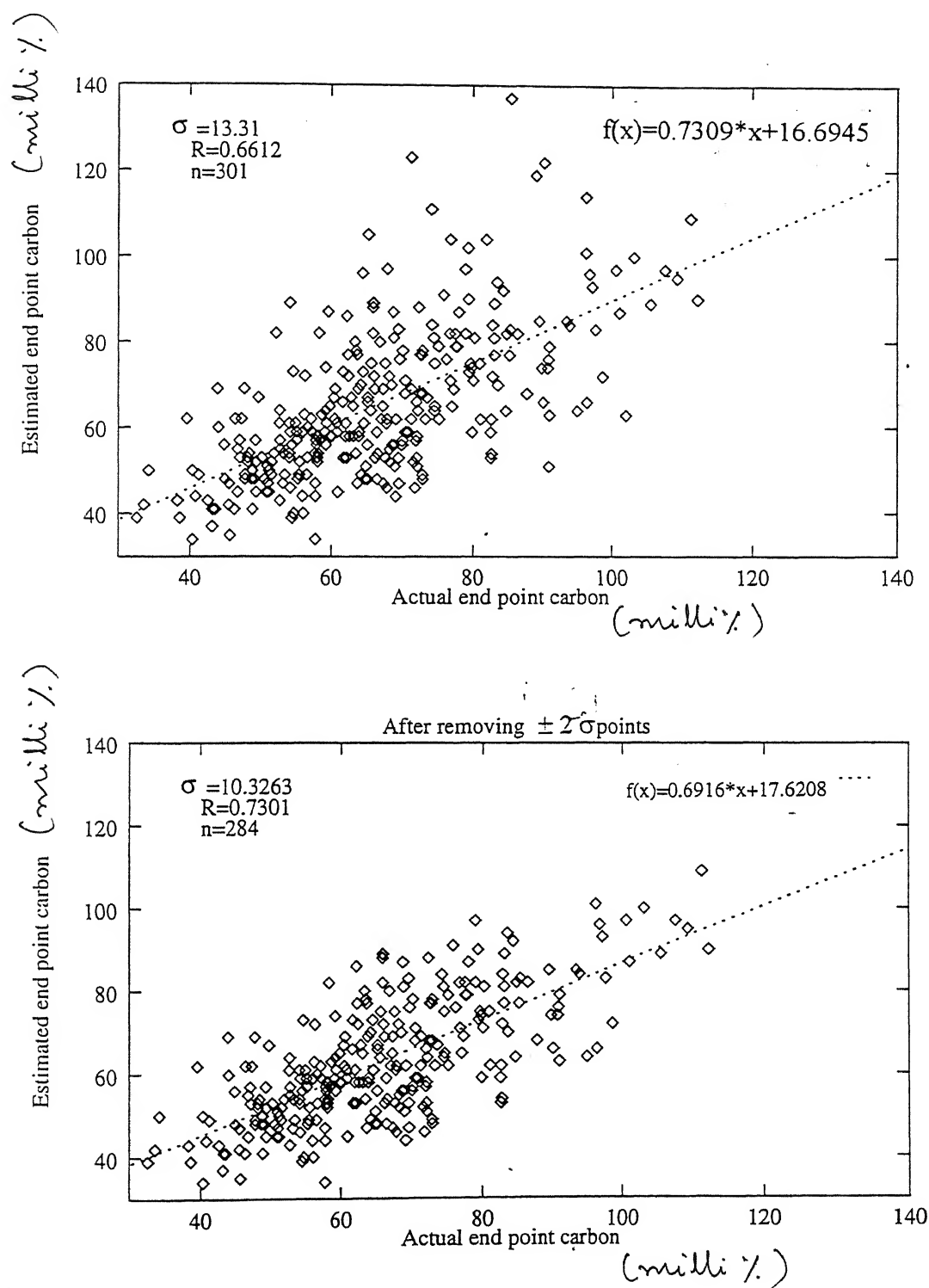


Fig. 3. Actual end point carbon versus Estimated end point carbon for Model No. (3)

For the regression curve	Before $\pm 2 \sigma$	After $\pm 2 \sigma$
$Y = mx$	$n = 301$ $m = 0.96853$ $\sigma = 13.8538$ $R = 0.66119$ $F = 6865$	$n = 286$ $m = 0.95147$ $\sigma = 11.2682$ $R = 0.7349$ $F = 9373$
$Y = mx + C$	$n = 301$ $m = 0.7309$ $C = 16.6945$ $\sigma = 13.31$ $R = 0.6612$ $F = 232$	$n = 284$ $m = 0.6916$ $C = 17.6208$ $\sigma = 10.3263$ $R = 0.7301$ $F = 321$

As shown above, standard deviation is decreased from 11.4872 (In Model No.2 for  $y=mx$ ) to 11.2682 in Model No.3 by incorporating mean values of operational variables in MLR equation. It is therefore proven that by incorporating mean values of operational variables in the regression a slightly better result can be obtained.

### 3.2.3 Sublance Model Based on Mass transport Control

On integrating Eq (2.5) from  $C_{SL}$  to  $C_t$ , we get

$$-\ln\left(\frac{C_t}{C_{SL}}\right) = k_c \cdot \frac{A}{V} \cdot t \quad (3.4)$$

$$\text{Or} \quad -\ln\left(\frac{C_t}{C_{SL}}\right) = K \cdot t \quad (3.5)$$

where  $K = k_c \cdot \frac{A}{V}$

$C_t$  =end point carbon content

$C_{SL}$  = carbon content at sub lance measurement

and  $t$  = time to reduce from  $C_i$  to  $C_{SL}$

The term  $k_c.A/V$  is actually called 'the capacity coefficient of mass transfer' and is usually represented by  $K$ . This  $K$  is specific to a converter practice at a particular plant.

The value of  $K$  may depend upon lance nozzle design, lance height, slag volume and composition, coolant additions in the converter, etc. In the present work, owing to the complicated nature of process we will be concerned with the overall value of  $K$  and not the individual values of the terms  $k_c$ ,  $A$  and  $V$ . This is because the phenomena of recirculation of metal in jet impact zone, droplet disintegration (due to the evolution of CO gas) as well as droplet coalescence during their passage in slag is still not well understood. Droplet disintegrates into hundreds of minute droplets (sparking), as visually observed during entire converter operation. Coalescence of droplets would also depend upon the inter-collision of droplets during their zig zag passage through the foamy slag.

In the present work two methods have been adopted to incorporate the effect of operational conditions on decarburization.

#### Method 1 :

It is assumed that 'K' is directly dependent upon the different operational variables. Multiple linear regression with different operational variables is first done as follows.

First 'K' is estimated for each heat from the equation

$$K = \frac{-\ln\left(\frac{C_t}{C_{SL}}\right)}{t} \quad (3.6)$$

The value of 'K' for each heat is then related to the operational data by

$$K = a_0 + \sum_{i=1}^n a_i . x_i \quad (3.7)$$

where,

$X_i$  = operational variables

$a_i$  = regression coefficients

$a_0$  = regression constant

The calculated value of 'K' is substituted back in

$$C_t = C_{SL} . \exp(-K.t) \quad (3.8)$$

to estimate the end point carbon.

### **Method 2 :**

In this method , Eq (3.12) is modified as

$$-\ln\left(\frac{C_t}{C_{SL}}\right) = K.t + \left(a_0 + \sum_{i=1}^n a_i . x_i\right) \quad (3.9)$$

and the regression is done for all the heats to obtain values of  $K$ ,  $a_0$  and  $a_i$ . Then  $C_t$  is estimated from

$$C_t = C_{SL} \cdot \exp \left[ -K \cdot t + \left( a_0 + \sum_{i=1}^n a_i \cdot x_i \right) \right] \quad (3.10)$$

In both the above mentioned methods, selection of operational variables is a critical step. For this “stepwise regression method” is used. This technique selects only the variables which are significant in affecting the dependent variable.

In the above equations the variable ‘time’ for each heat is calculated in two ways.

$$time = \frac{\text{oxygen.blown.in.the.second.blow}}{\text{oxygen.flow.rate}} \quad (3.11)$$

In an alternative approach the time is normalized for total iron content of bath by assuming that scrap contains approximately 100% Fe and hot metal contains approximately 92% Fe.

$$time = \frac{\text{oxygen.blown.in.the.second.blow} \cdot \text{Total Wt.of bath}}{\text{oxygen.flow.rate} \cdot (\text{Wt.of bath} \cdot 0.92 + \text{Wt.of scrap})} \quad (3.12)$$

These two methods are applied to plant (1) data set first. Then after deciding the method which gives a better result, that method is applied to the Data sets 2-4.

### 3.2.3.1 Application of Method 1 for plant Data set 1 :

As summarized below, K is related to six operational variables. The selected variables are only basicity ( $X_3$ ) and ore added during end blow ( $X_5$ ), as shown below.

#### Model No. 4 :

Dependent variable in the regression	Independent variables considered for the regression	Selected variables by stepwise regression and their corresponding coefficients
K	$X_1$ = Temperature at subblance $X_2$ = Second blow additions $X_3$ = Basicity $X_4$ = Ore added during end blow $X_6$ = Hot ratio	$X_1$ =Basicity ( $a_1 = -0.000215759$ ) $X_5$ = ore added ( $a_5 = -0.000000635$ ) Regression constant ( $a_0 = 0.10422$ )

With these selected variables ' K ' values are calculated by substituting the coefficients listed above as follows.

$$K = a_0 + \sum_{i=1}^2 a_i \cdot x_i \quad (3.6)$$

$$K = 0.10422 - 0.000215759(3.9990) + 0.000000635(1004)$$

$$= 0.10399$$

These ' K ' values are substituted in Eq (3.8) to estimate the end point carbon values.

The regression between estimated end point carbon and actual end point carbon has been

done. The results are as follows. The plot of actual end point carbon versus estimated end point carbon has been shown in Fig (4).

For the regression curve	before $\pm 2 \sigma$	after $\pm 2 \sigma$
$Y = mx$	$n = 301$ $m = 0.496$ $\sigma = 13.33$ $R = 0.6627$ $F = 7046$	$N = 288$ $m = 0.96759$ $\sigma = 11.43$ $R = 0.7315$ $F = 9130$

The result obtained here i.e. by sublance model ( $\sigma = 13.33$  milli %) is better than obtained by exponential model ( $\sigma = 14.002$  milli % in Model No.1) for the same data set. It may be noted that only 3 data points are discarded for data points lying outside  $\pm 2 \sigma$  limits.

#### Model No . 5 :

If lance life is included in the regression, it is found that a slight improvement in results can be obtained.

Dependent variable in the regression	Independent variables considered for the regression	Selected variables by stepwise regression and their corresponding coefficients
K	$X_1$ =lance life $X_2$ = Temperature at sublance $X_3$ = Second blow additions $X_4$ = Basicity $X_5$ = Ore added during end blow $X_6$ = Hot ratio	$X_1$ =lance life ( $a_1 = 0.000003467$ ) $X_5$ = ore added ( $a_5 = -0.000000683$ ) $X_4$ =basicity ( $a_4 = -0.000219421$ ) Regression constant ( $a_0 = 0.10135$ )



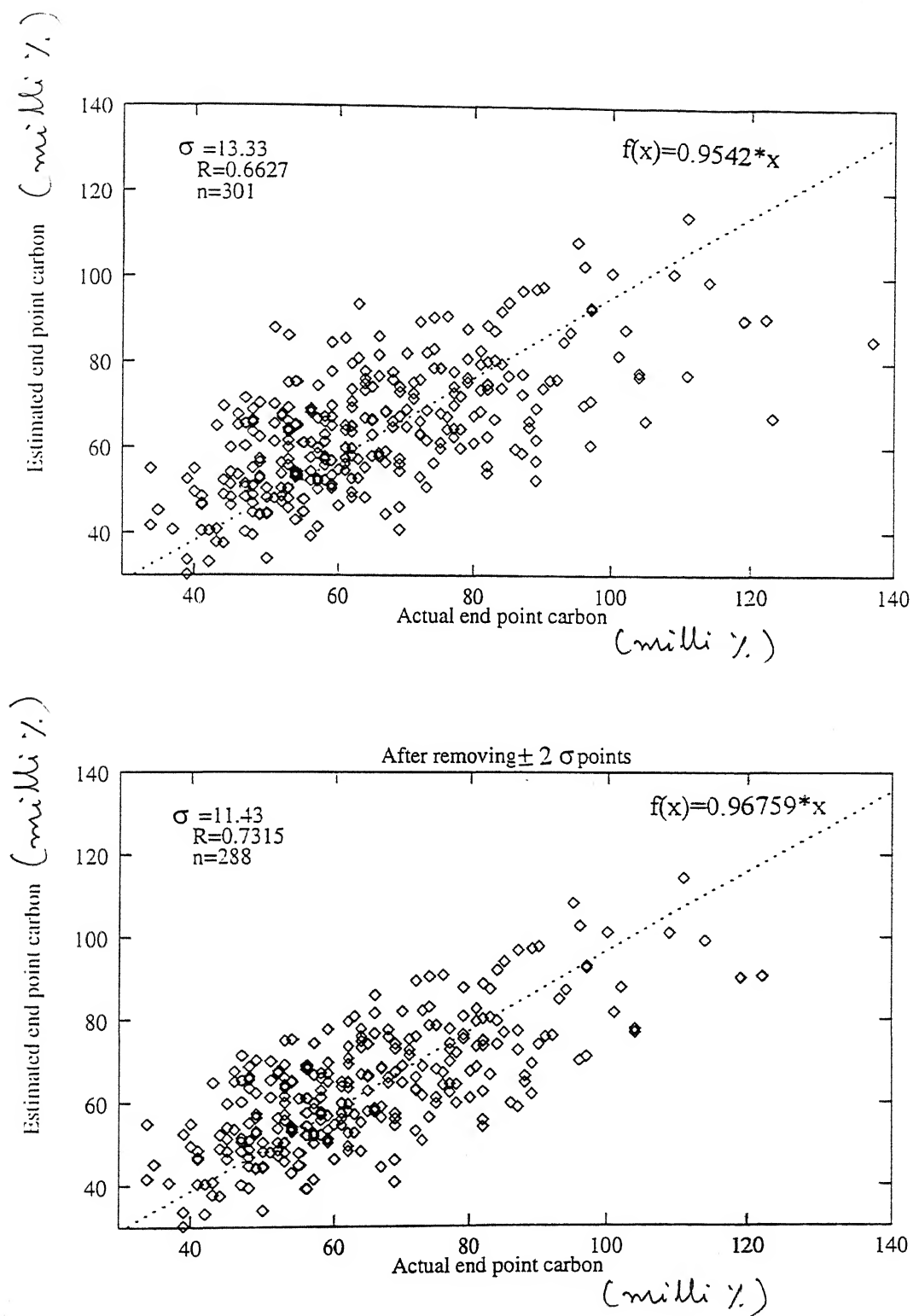


Fig.4. Actual end point carbon versus Estimated end point carbon for Model No.(4)

With these selected variables ' K ' values are calculated by substituting the coefficients in MLR Eq (3.6) as follows.

$$K = a_0 + \sum_{i=1}^3 a_i . x_i$$

$$K=0.10135-0.000003467(30)+0.000000683(1004)-0.000219412(3.9990)$$

$$=0.10105$$

These ' K ' values are substituted in Eq (3.8) to estimate the end point carbon values. The regression between estimated end point carbon and actual end point carbon has been done. The details are as follows.

For the regression curve	Before $\pm 2 \sigma$
Y = mx	n = 301 m = 0.95390 $\sigma = 13.173$ R = 0.6688 F = 7211

#### Model No. 6 :

If the variable basicity is replaced with slag volume to see the affect, the result obtained is as follows.

Dependent variable in the regression	Independent variables considered for the regression	Selected variables by stepwise regression and their corresponding coefficients	Regression of estimated Vs. Actual end point carbon. ( $y=mx$ )
K	$X_1$ =lance life $X_2$ = Temperature at subblance $X_3$ = Second blow additions $X_4$ = slag volume $X_5$ = Ore added during end blow $X_6$ = Hot ratio	$X_1$ =lance life ( $a_1 = 0.009085$ ) $X_5$ = ore added ( $a_5 = 0.000003288$ ) Regression constant ( $a_0 = 0.009085$ )	$m=0.95329$ $\sigma =13.522$ $R=0.6497$ $F=6834$

As shown above , '  $\sigma$  ' is increased from 13.173 to 13.522 (when compared with Model No. (5 )). Thus incorporation of ' basicity ' as independent variable gives better result than that of ' slag volume'. In subsequent Models only basicity will be used to estimate end point carbon but not the slag volume.

### 3.2.3.2 Application of Method 2 for plant Data set 1 :

In this method, the term ' $-\ln(C_t / C_{SL})$ ' is related to the following operational variables.

#### Model No. 7 :

Dependent variable in the regression	Independent variables considered for the regression	Selected variables by stepwise regression and their corresponding coefficients
$-\ln(C_t / C_{SL})$	$X_1$ =time $X_2$ = Temperature at subblance $X_3$ = Second blow additions $X_4$ = Basicity $X_5$ = Ore added during end blow $X_6$ = Hot ratio	$X_1$ =time ( $K = 0.007827967$ ) $X_5$ = ore added ( $a_5 = 0.000114356$ ) $X_4$ =basicity ( $a_4=-0.040036131$ ) Regression constant ( $a_0 = 0.473776$ )

With these selected variables  $-\ln\left(\frac{C_t}{C_{SL}}\right)$  is calculated by substituting the coefficients  $K$ ,  $a_0$  and  $a_i$  in MLR Eq (3.9) as follows.

$$-\ln\left(\frac{C_t}{C_{SL}}\right) = K.t + \left(a_0 + \sum_{i=1}^3 a_i.x_i\right)$$

$$\begin{aligned} -\ln\left(\frac{C_t}{C_{SL}}\right) &= 0.007827967(152) + (0.473776 + 0.000114356(1004) - 0.040036131(3.99)) \\ &= 1.618 \end{aligned}$$

From these  $-\ln\left(\frac{C_t}{C_{SL}}\right)$  values, ' $C_t$ ' values are calculated as follows.

$$-\ln\left(\frac{C_t}{C_{SL}}\right) = 1.618$$

From Eq (3.10)

$$\begin{aligned} C_t &= C_{SL} \cdot \exp(-1.618) \\ &= 257 \cdot \exp(-1.618) \\ &= 50.926 \end{aligned}$$

The plot of actual end point carbon versus estimated end point carbon has been shown in Fig (5). The estimated end point carbon values are then regressed with actual ones and the results of regression are as follows.

For the regression curve	Before $\pm 2 \sigma$	After $\pm 2 \sigma$
$Y = mx$	$n = 301$ $m = 0.95311$ $\sigma = 12.9347$ $R = 0.66582$ $F = 7466$	$n = 289$ $m = 0.97334$ $\sigma = 11.027$ $R = 0.73165$ $F = 9867$
$Y = mx + C$	$n = 301$ $m = 0.496$ $C = 32.0134$ $\sigma = 9.8615$ $R = 0.6658$ $F = 238$	$n = 282$ $m = 0.497$ $C = 31.4141$ $\sigma = 8.3363$ $R = 0.7138$ $F = 290$

It can be observed that the ' $\sigma$ ' obtained in this model (12.9347) is less than, the ' $\sigma$ ' obtained (13.33) by the first method (Model No. 4). It can therefore be concluded that method (2) gives a better result than method (1).

#### Model No. 8 :

If lance height is included in the regression, we get a slightly better prediction.

Dependent variable in the regression	Independent variables considered for the regression	Selected variables by stepwise regression and their corresponding coefficients
$-\ln(C_t / C_{SL})$	$X_1$ =time $X_2$ = Temperature at sublance $X_3$ = Second blow additions $X_4$ = Basicity $X_5$ = Ore added during end blow $X_6$ = Hot ratio $X_7$ =lanceheight	$X_1$ =time ( $K = 0.0078753$ ) $X_5$ = ore added ( $a_5 = 0.0001102$ ) $X_4$ =basicity ( $a_4=-0.0466949$ ) $X_7$ =lanceheight ( $a_7=-0.0066976$ ) Regression constant ( $a_0 = 2.013246$ )

With these selected variables ' $-\ln\left(\frac{C_t}{C_{SL}}\right)$ ' is calculated by substituting the coefficients  $K$ ,  $a_0$  and  $a_i$  in MLR Eq (3.9) as follows.

$$-\ln\left(\frac{C_t}{C_{SL}}\right) = K.t + \left(a_0 + \sum_{i=1}^4 a_i .x_i\right)$$

$$\begin{aligned}
 -\ln\left(\frac{C_t}{C_{SL}}\right) &= 0.0078753(152) + (2.013246 - 0.0066976(227) + 0.0001102(1004) - \\
 &\quad 0.04669496(3.99)) \\
 &= 1.61426
 \end{aligned}$$

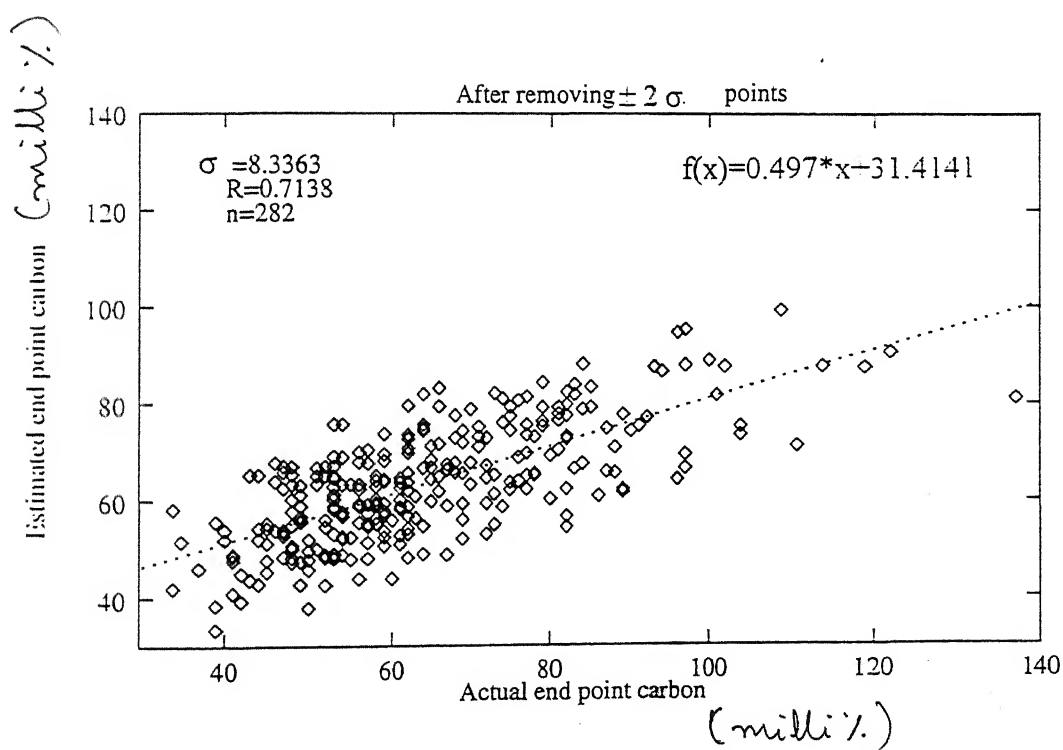
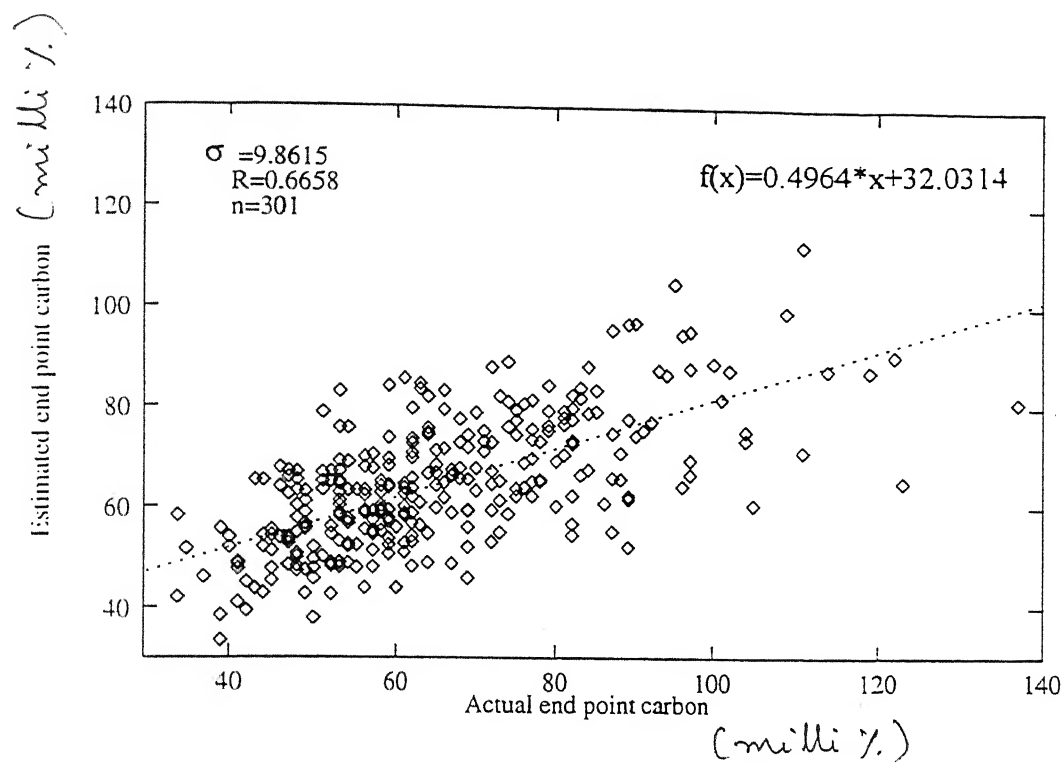


Fig 5. Actual end point carbon versus Estimated end point carbon for Model No. (7)

From these  $-\ln\left(\frac{C_t}{C_{SL}}\right)$  values, ' $C_t$ ' values are calculated as follows.

$$-\ln\left(\frac{C_t}{C_{SL}}\right) = 1.61426$$

From Eq (3.10)

$$\begin{aligned} C_t &= C_{SL} \cdot \exp(-1.61426) \\ &= 257 \cdot \exp(-1.61426) \\ &= 51.15252 \end{aligned}$$

The estimated end point carbon values are regressed with actual ones. The results of regression are as follows.

For the regression curve	Before $\pm 2 \sigma$	After $\pm 2 \sigma$
$Y = mx$	$n = 301$ $m = 0.95856$ $\sigma = 11.816$ $R = 0.73992$ $F = 8226$	$n = 261$ $m = 0.98009$ $\sigma = 10.012$ $R = 0.79227$ $F = 11022$
$Y = mx + C$	$n = 272$ $m = 0.5692$ $C = 27.3729$ $\sigma = 9.333$ $R = 0.7399$ $F = 326$	$n = 259$ $m = 0.5977$ $C = 25.5638$ $\sigma = 8.092$ $R = 0.7784$ $F = 395$

It can be observed that the '  $\sigma$  ' obtained (8.092) with lance height as a variable is less than, the '  $\sigma$  ' obtained (8.3363) in Model No. (7) i.e. without lance height. So, it is concluded that with the known lance height values, better estimation can be done.

#### **Model No. 9 :**

As a further step to improve the estimation of end point carbon, the equilibrium concentration of carbon ( $C_e$ ) is incorporated in the LHS of the MLR equation i.e. the MLR Eq(3.9) is modified as

$$-\ln\left(\frac{C_t - C_e}{C_{SL} - C_e}\right) = K.t + \left(a_0 + \sum_{i=1}^n a_i.x_i\right) \quad (3.13)$$

and the regression is done for all the heats to obtain values of  $K$ ,  $a_0$  and  $a_i$ . Then ' $C_t$ ' is estimated from

$$C_t = C_e + \left\{ (C_{SL} - C_e) \exp \left[ - \left( K.t + \left[ a_0 + \sum_{i=1}^n a_i.x_i \right] \right) \right] \right\} \quad (3.14)$$

The term  $-\ln\left(\frac{C_t - C_e}{C_{SL} - C_e}\right)$  is related to the following operational variables.



Dependent variable in the regression	Independent variables considered for the regression	Selected variables by stepwise regression and their corresponding coefficients
$-\ln\left(\frac{C_t - C_e}{C_{SL} - C_e}\right)$	$X_1$ =time $X_2$ = Temperature at sublance $X_3$ = Second blow additions $X_4$ = Basicity $X_5$ = Ore added during end blow $X_6$ = Hot ratio	$X_1$ =time ( $K = 0.00855417$ ) $X_5$ = ore added ( $a_5 = 0.000118546$ ) $X_4$ =basicity ( $a_4=-0.04342846$ ) Regression constant ( $a_0 = 0.505659$ )

With these selected variables  $-\ln\left(\frac{C_t - C_e}{C_{SL} - C_e}\right)$  is calculated by substituting the coefficients  $K$ ,  $a_0$  and  $a_i$  in MLR Eq (3.13) as follows.

$$\begin{aligned}
 -\ln\left(\frac{C_t - C_e}{C_{SL} - C_e}\right) &= K.t + \left(a_0 + \sum_{i=1}^3 a_i .x_i\right) \\
 &= 0.00855417(152) + 0.505659 + 0.000118546(1004) - 0.04342846(3.99) \\
 &= 1.75163
 \end{aligned}$$

From Eq (3.14)

$$\begin{aligned}
 C_t &= C_e + [(C_{SL} - C_e) \exp(-1.75163)] \\
 &= 10 + [(257-10) \cdot \exp(-1.75163)] \\
 &= 52.8521
 \end{aligned}$$

The estimated end point carbon values are regressed with actual ones. The plots are shown in Fig (6). The results of regression are as follows.

For the regression curve	Before $\pm 2 \sigma$	After $\pm 2 \sigma$
$Y = mx$	$n = 301$ $m = 0.94268$ $\sigma = 12.6652$ $R = 0.66826$ $F = 7618$	$n = 286$ $m = 0.96702$ $\sigma = 10.5013$ $R = 0.73212$ $F = 10511$
$Y = mx + C$	$n = 301$ $m = 0.4428$ $C = 35.0092$ $\sigma = 8.7458$ $R = 0.6683$ $F = 241$	$n = 286$ $m = 0.45$ $C = 34.1851$ $\sigma = 7.613$ $R = 0.712$ $F = 291$

It can be observed that the ' $\sigma$ ' obtained here (7.613) is less than, the ' $\sigma$ ' obtained (8.3363) in Model No.(7) for the same set of data. Thus, it is proven that better estimation of end point

carbon can be done by using the term  $-\ln\left(\frac{C_t - C_e}{C_{SL} - C_e}\right)$  i.e. considering the effect of  $C_e$

instead of using the term  $-\ln\left(\frac{C_t}{C_{SL}}\right)$

#### Model No. 10 :

If lance height is included in the regression, we obtain a better result (as explained in Model No. 8 )

For the regression curve	Before $\pm 2 \sigma$	After $\pm 2 \sigma$
$Y = mx$	$n = 272$ $m = 0.94839$ $\sigma = 11.61$ $R = 0.74384$ $F = 8341$	$n = 263$ $m = 0.96813$ $\sigma = 10.0727$ $R = 0.78413$ $F = 10739$
$Y = mx + C$	$n = 272$ $m = 0.517$ $C = 30.3324$ $\sigma = 8.3772$ $R = 0.7438$ $F = 334$	$n = 262$ $m = 0.5284$ $C = 29.3979$ $\sigma = 7.4204$ $R = 0.7728$ $F = 385$

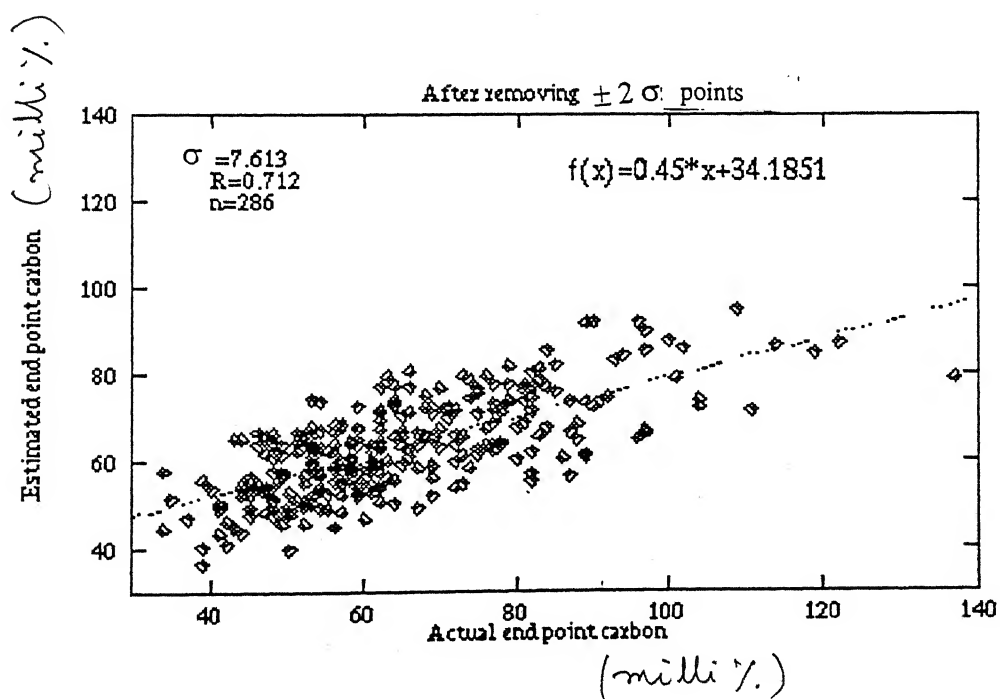
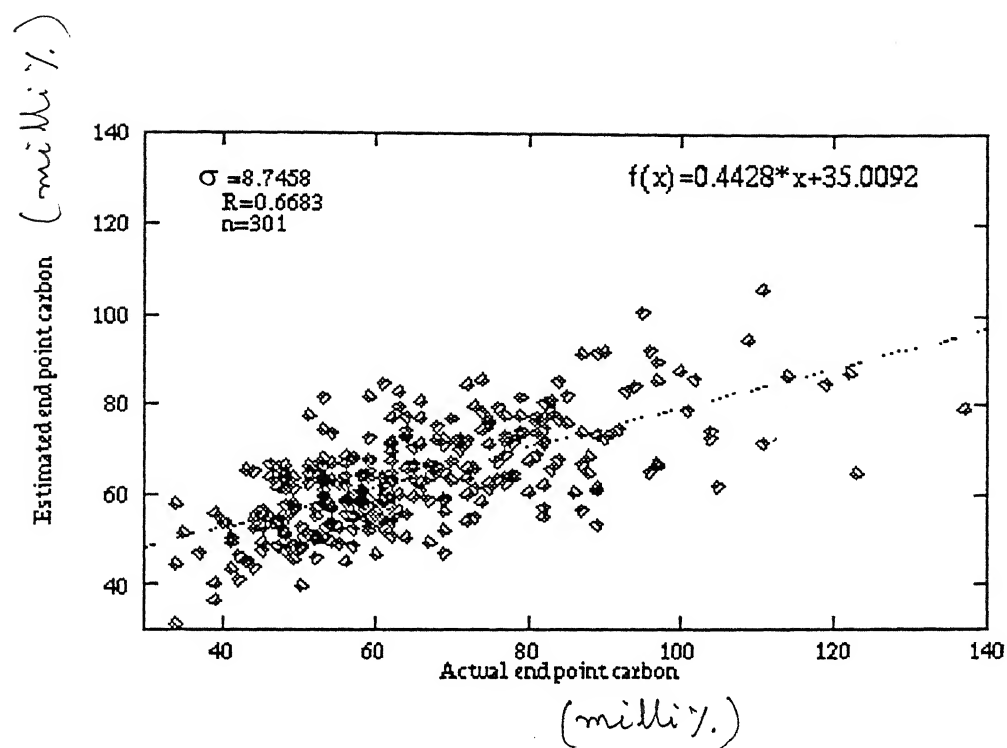


Fig. 6. Actual end point carbon versus Estimated end point carbon for Model No. (9)

### 3.2.3.3 Results for Data sets of plant (2), plant (3) and plant(4) :

It has been shown earlier that Model No.(9) based on Eq.(3.13), (modified equation suggested in method (2)) gives the best result. This method is now applied to estimate the end point carbon.

Results obtained for plant data sets (2) and (3) are summarized in Table No.(1) under Model No.(11), Model No.(12), respectively. It may be noted that the lance height details are not available in data sets (2) and (3). Otherwise, by using lance height variable in the regression, a lower standard deviation in estimating the end point carbon could have been achieved. It can also be observed that '  $\sigma$  ' for plant data set (2) is lower than for plant data set (1). This is because, the plant ( 2 ) data set has more number of data points(1744 data Vs. 301 data).

The results of carbon prediction for plant 4 data set are summarized in Model No.(13) and Model No. (14), in Table (1). In this set of plant data, carbon is predicted for only for those heats in which end point carbon is less than 0.06 %C. The standard deviation for plant 4 data set is highest because of the fact that bottom stirring was absent.

### 3.2.3.4 Application of Temperature Model

As explained in Chapter (2), N.Bessho et al. have given a model, Eq(2.33), to estimate end point temperature

$$T_f = T_{sl} + P(\Delta O_2) + Q \left( \frac{1}{C_f} - \frac{1}{C_{sl}} \right) + R$$

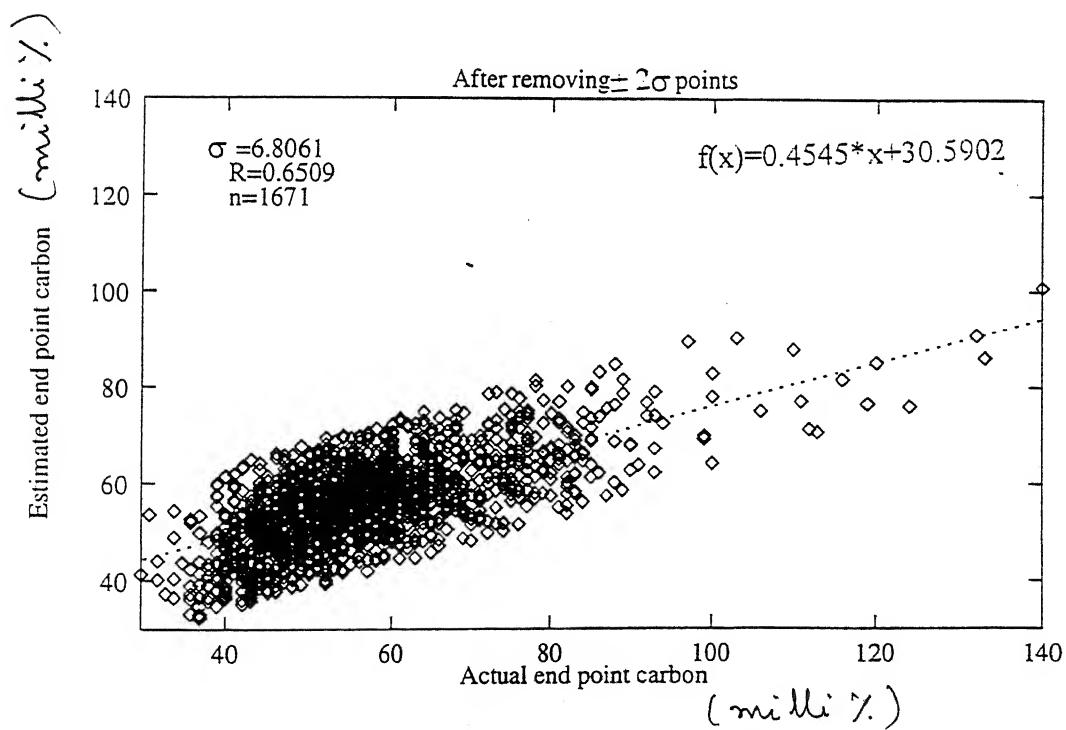
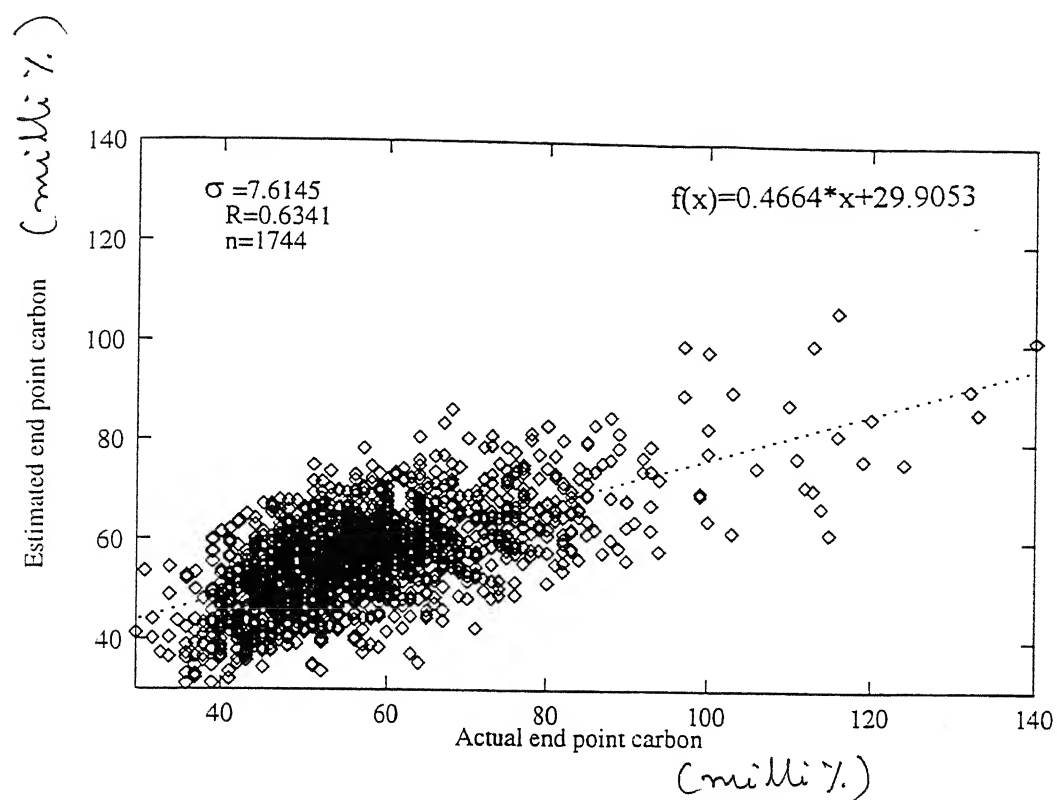


Fig 7. Actual end point carbon versus Estimated end point carbon for Model No.11

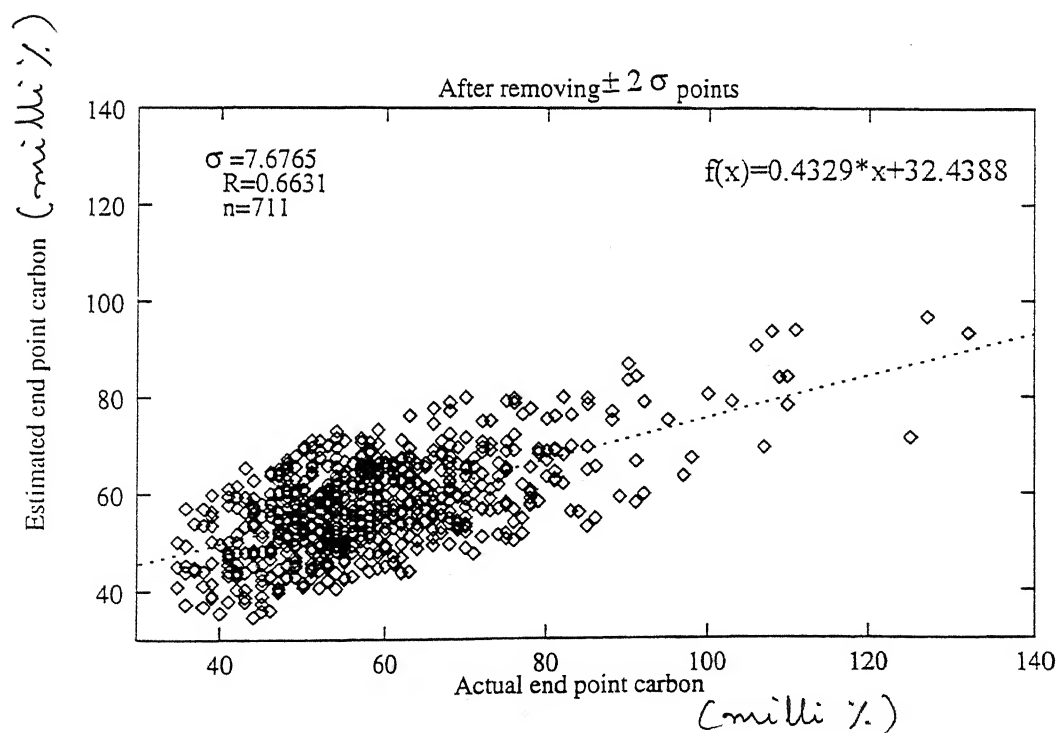
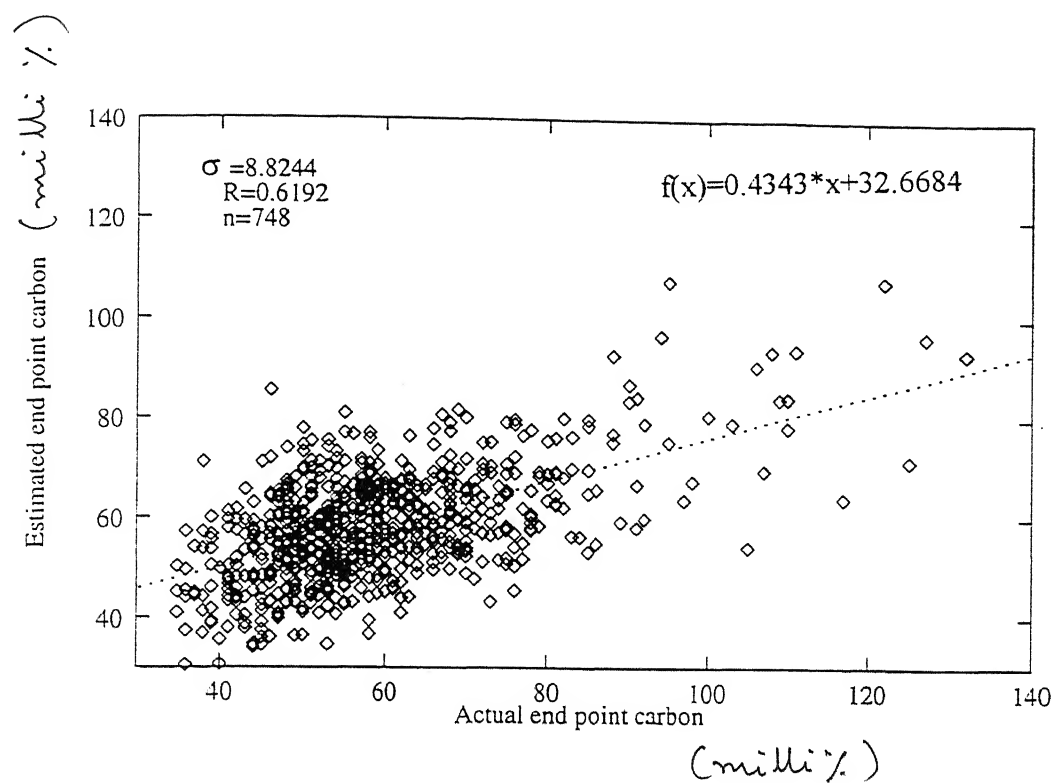
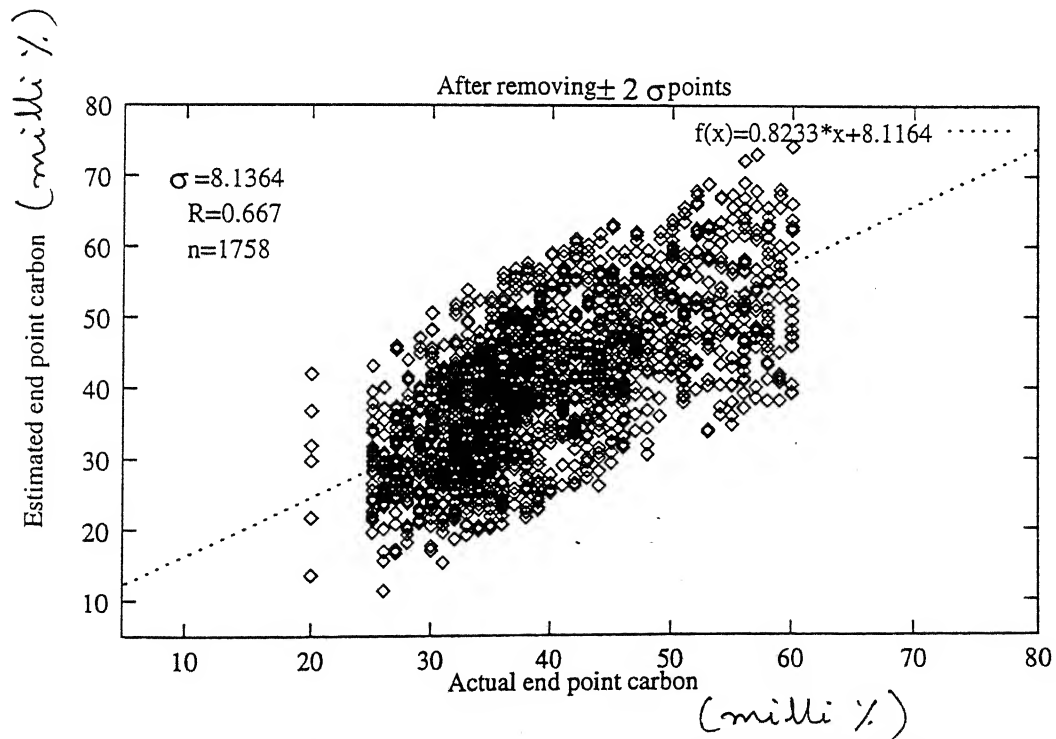
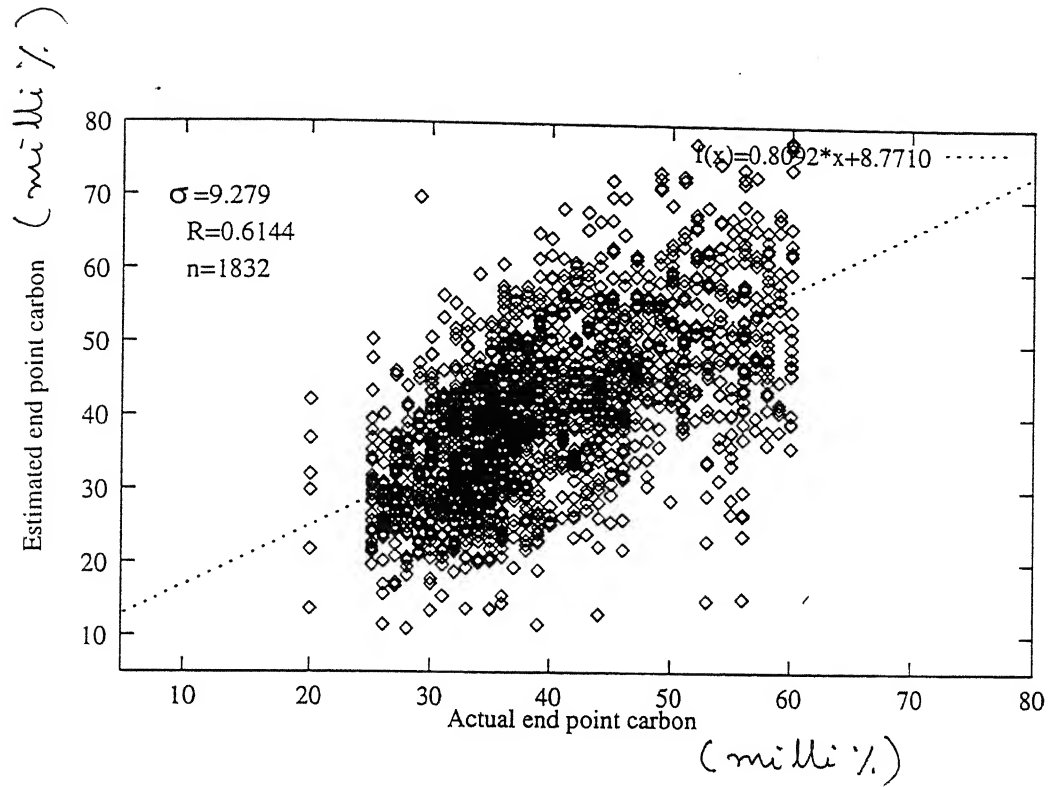


Fig 8 . Actual end point carbon versus Estimated end point carbon for Model No.12



9 Actual end point carbon versus Estimated end point carbon for Model No.14

This model is applied in the present work to estimate the end point temperature by taking different combinations of operational variables which may effect the end point temperature. Various alternatives have been tried to estimate the end point temperature with the minimum possible standard deviation. The results of all the Models for plant data set 1 are summarized in Model Nos. (15),(16),(17), in Table (1).

In the above Eq(2.33), the end point carbon  $C_f$  is not known a priori at the time of subluance measurement. So, it is not correct to use this information to predict the end point temperature though it gives a good result. Therefore the equation is modified as

$$T_f = T_{sl} + P(\Delta O_2) + Q\left(\frac{1}{C_{sl}}\right) + R \quad (3.15)$$

This equation was applied to plant data set 1 to predict end point temperature and the results are summarized in Model No.(18),(19),(20),(21),(22), in Table (1).

The Eq(2.33) was applied to predict end point temperature by substituting the predicted end point carbon ( $C_f$ ) from the subluance carbon model in Model No.(23). The results are summarized in Table (1).

Similarly for plant data sets (2) and (3), Eq(3.15) is applied to predict the end point temperature. The results are summarized in Model No.(24) and Model No.(25), respectively, in Table (1).

For plant data set (4) , the end point temperature was also estimated from the equation (2.48) which was given by Byun et al.(as explained in Chapter (2)).

$$\Delta T_{cal} = \delta_1(C_{sl} - C_f) + \delta_2\left(\frac{1}{C_e} - \frac{1}{C_{sl}}\right) + \delta_3 \Delta O_2$$



The results are summarized in Model No.(26) in Table (1).

The earlier Model given by Bessho et al., Eq(2.33) was used to estimate the end point temperature by substituting the end point carbon estimated from the sublimation carbon Model No.(13). The results are summarized in Model No. (27) in Table (1).

### **3.3 Discussion**

Fundamental aspects of actual mechanism of decarburization (i.e. droplet versus bulk decarburization) are discussed in section 3.3.1. This is followed by comparative evaluation of the results obtained by using models for different sets of plant data in section 3.3.2.

#### **3.3.1 Estimation of mass transfer coefficient and droplet decarburization versus bulk metal decarburization**

The two possible mechanisms of decarburization are

- Decarburization via droplets ejected from the jet impact zone and
- Decarburization at the interface of bulk metal and slag and in the recirculation zone below the jet.

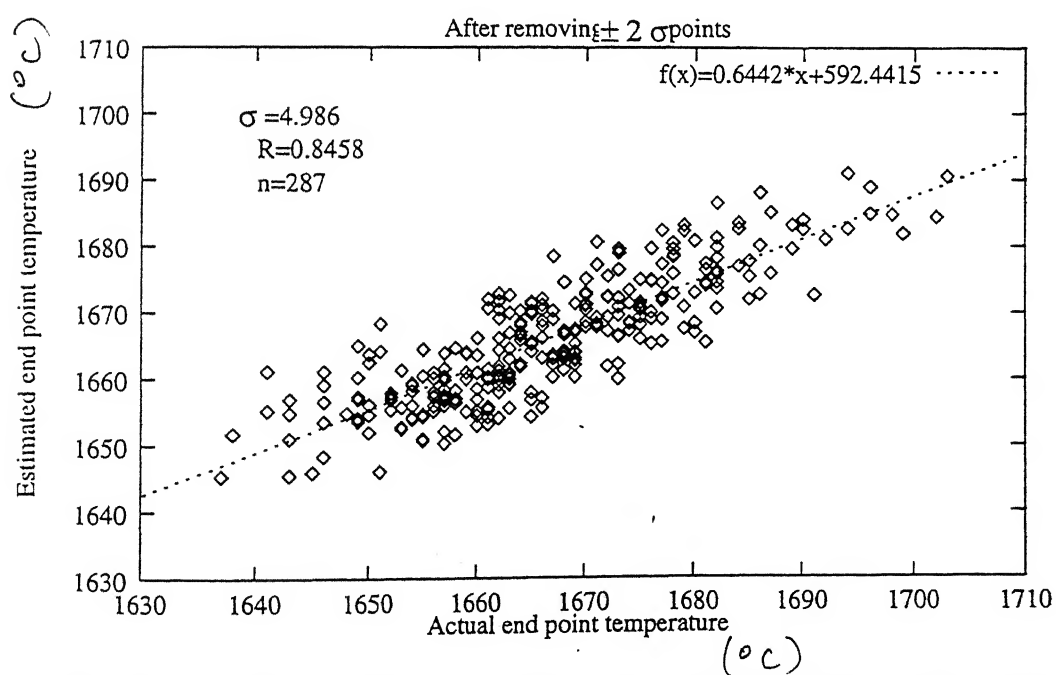
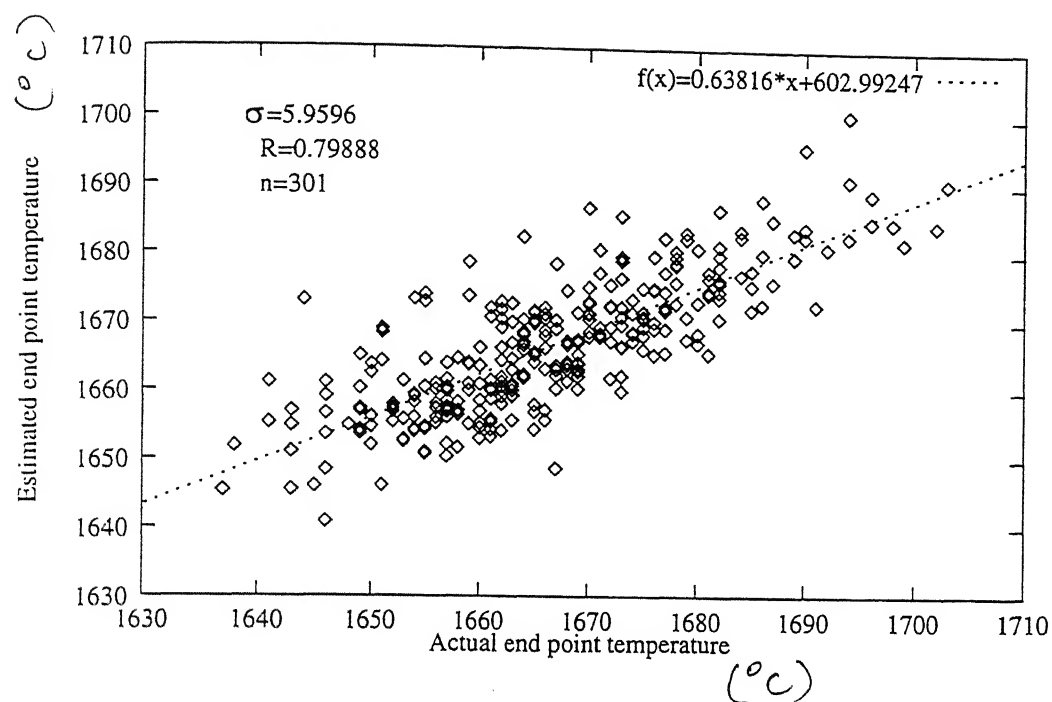


Fig 10. Actual end point temperature versus estimated end point temperature for Model No.15

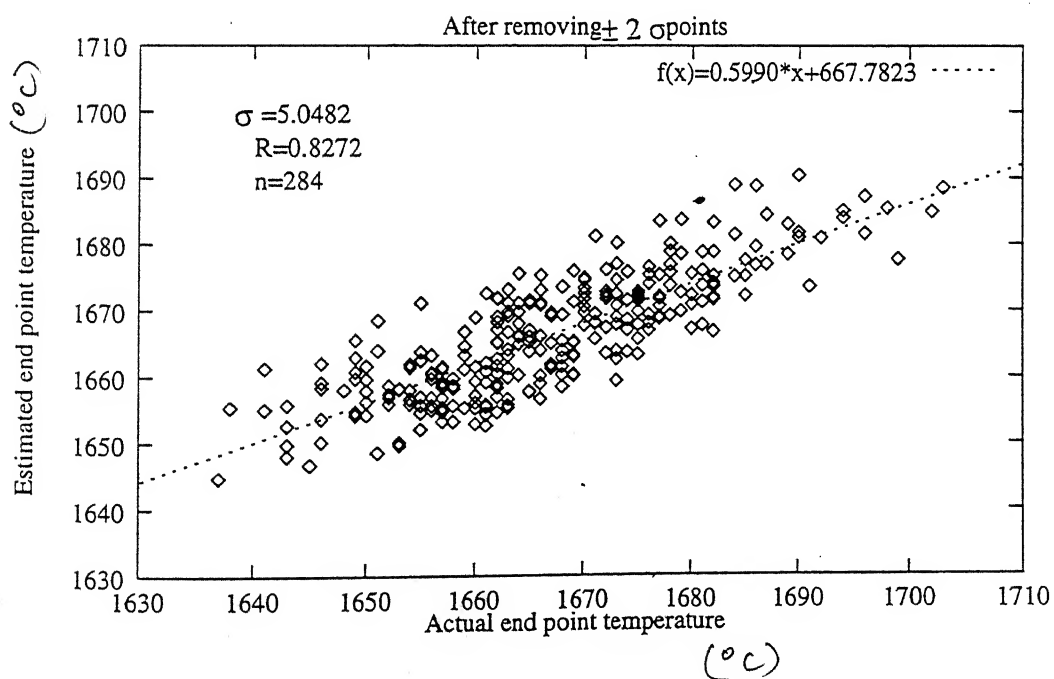
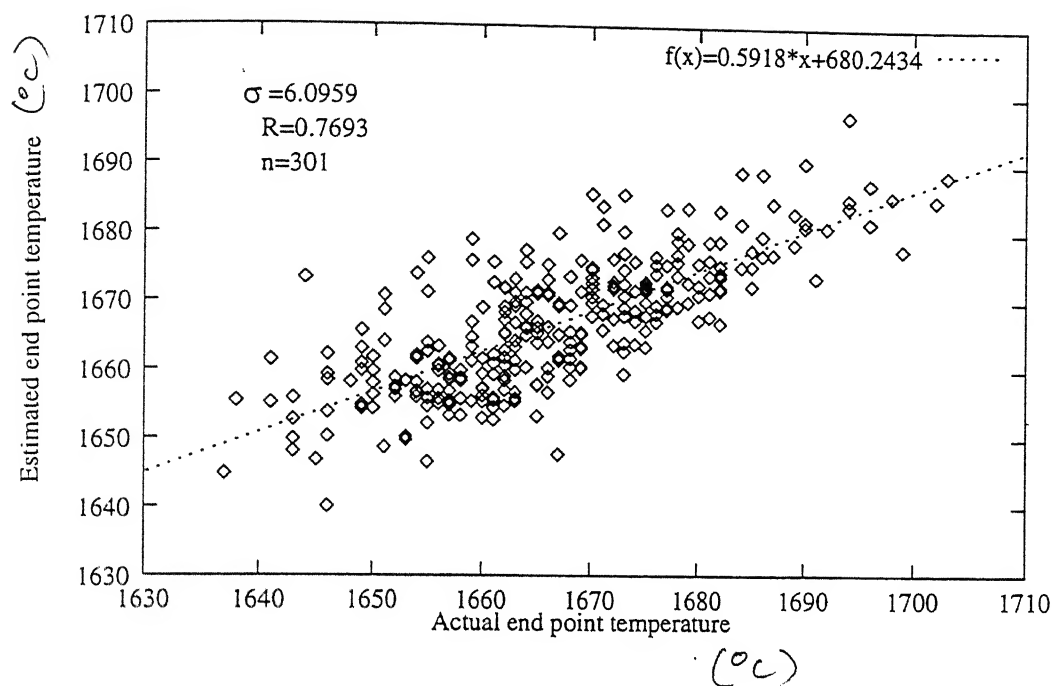


Fig 11. Actual end point temperature versus estimated end point temperature for Model No.20

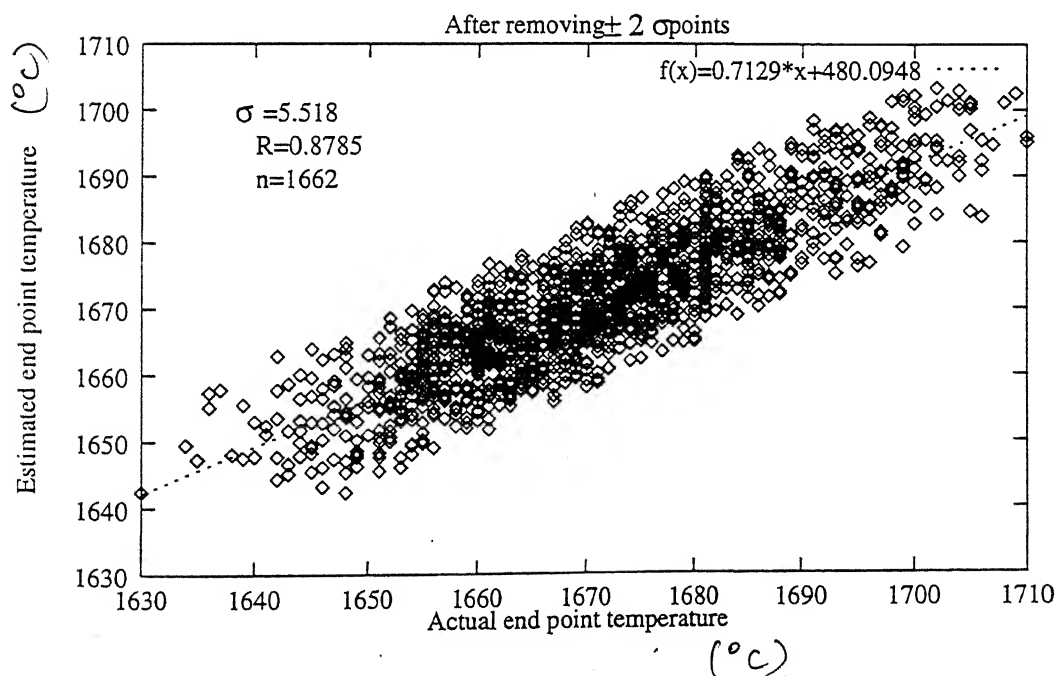
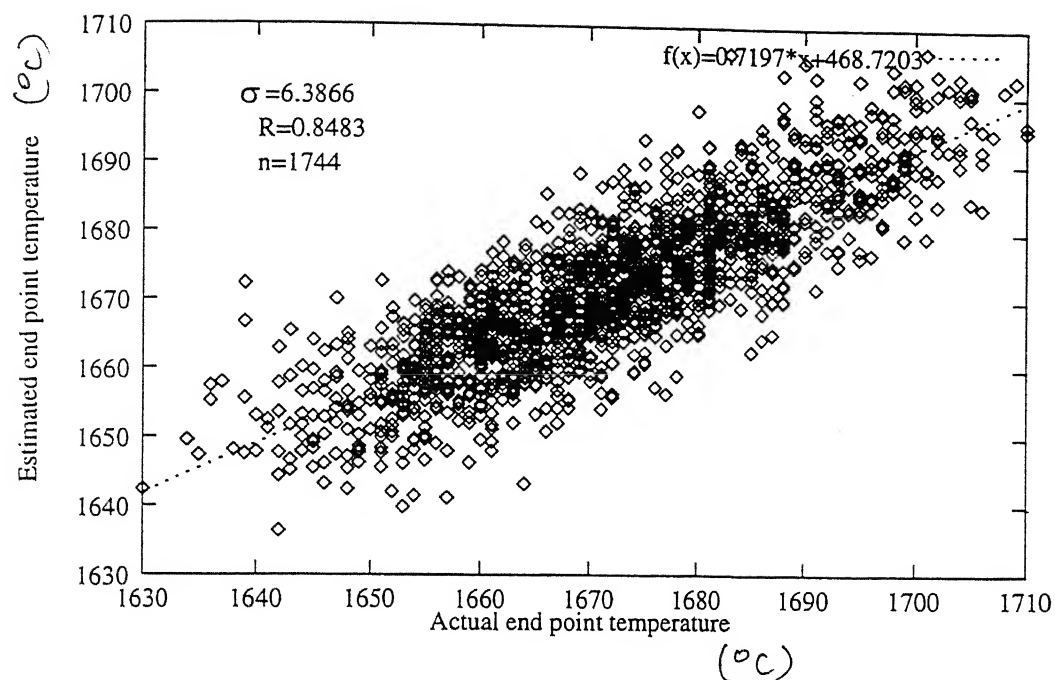


Fig 12. Actual end point temperature versus estimated end point temperature for Model No.24

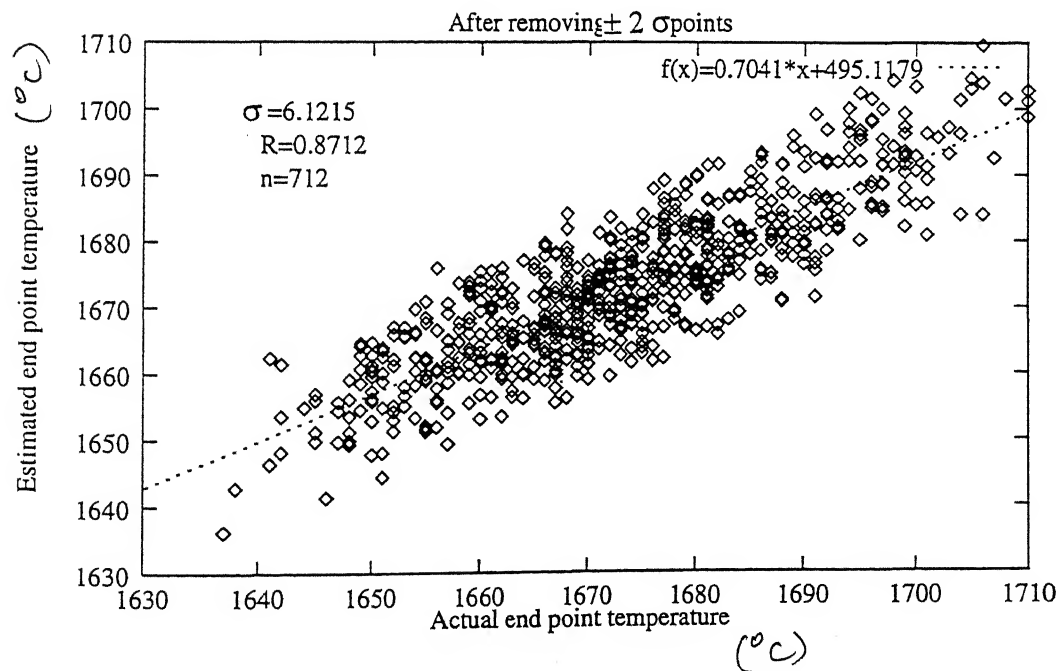
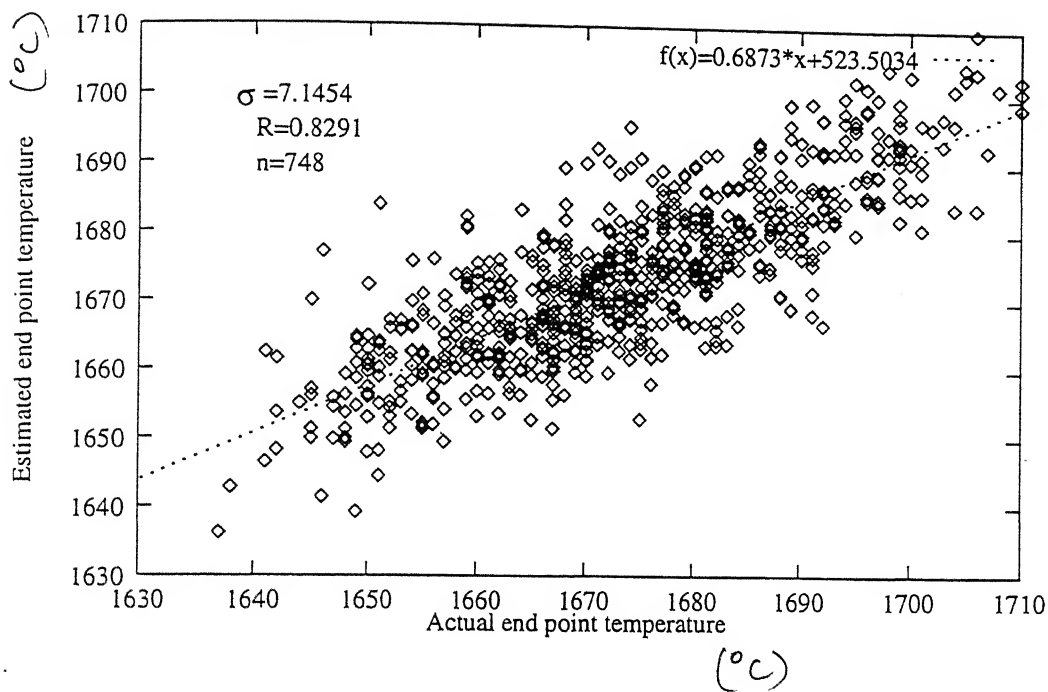


Fig 13. Actual end point temperature versus estimated end point temperature for Model No.25

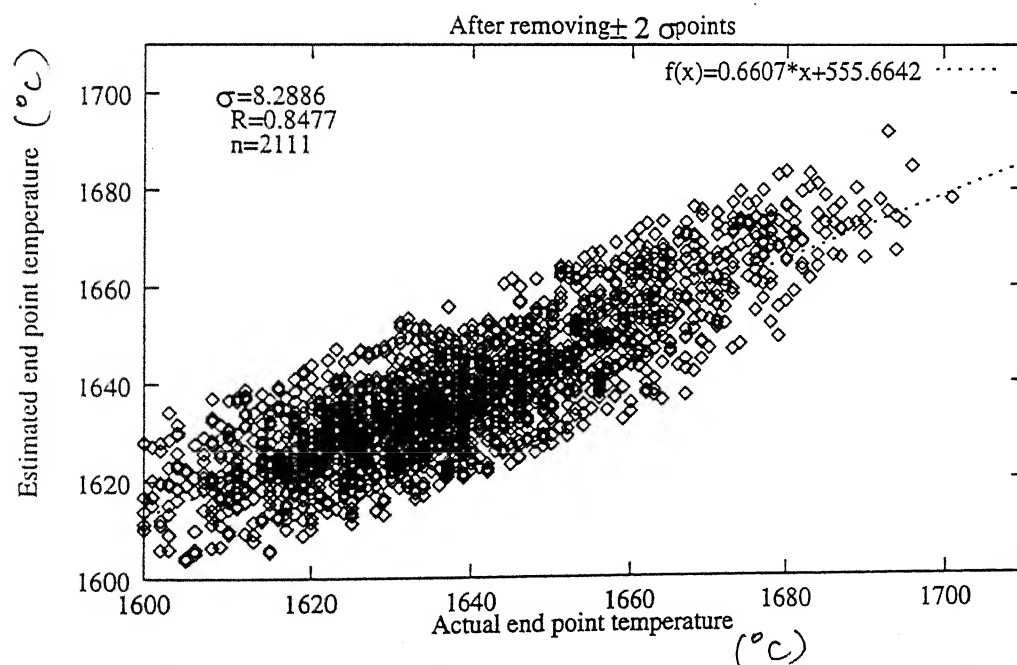
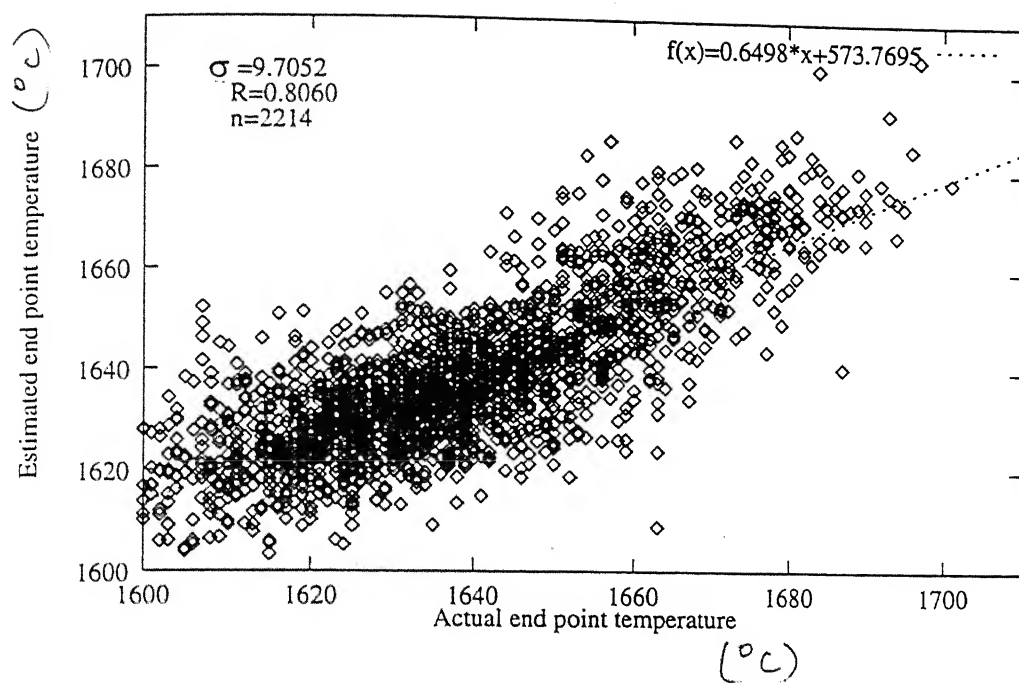


Fig 14. Actual end point temperature versus estimated end point temperature for Model No.26

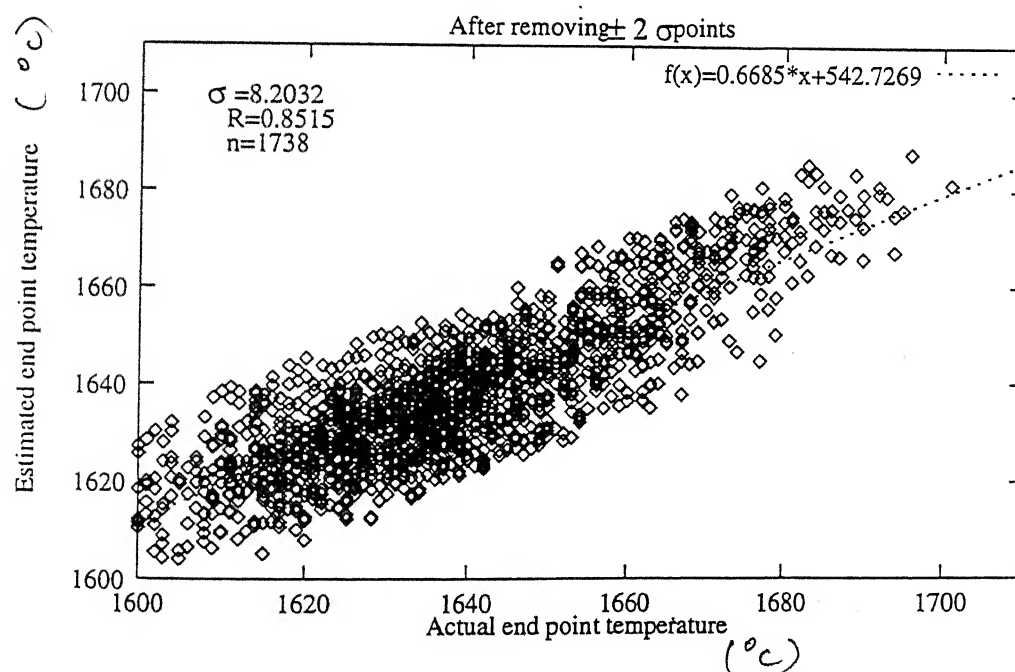
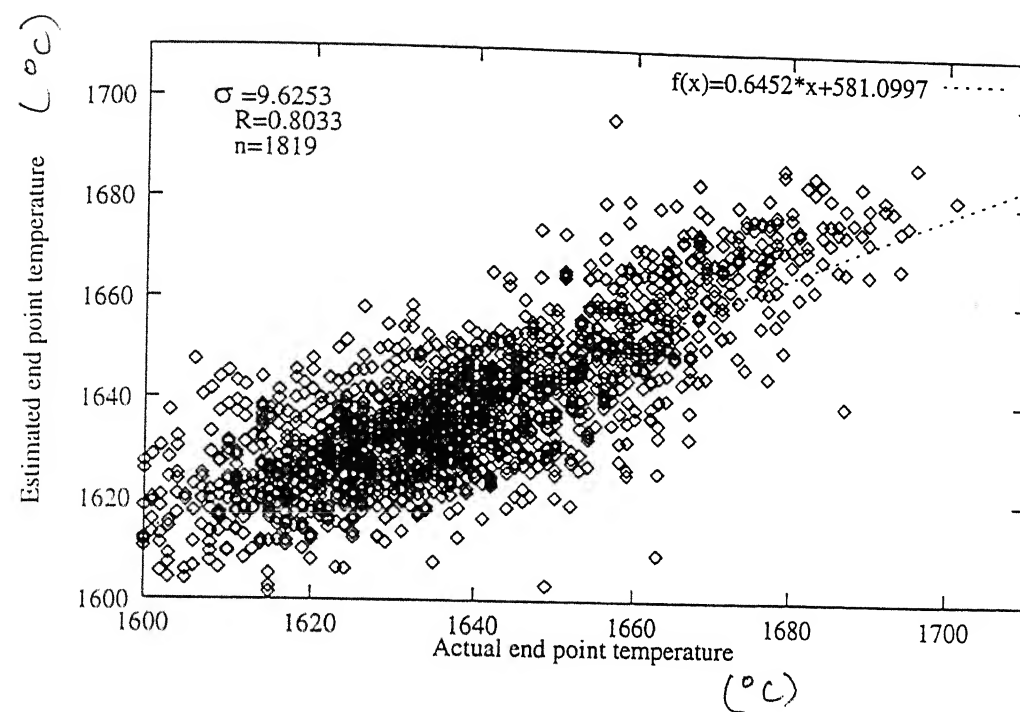


Fig 15. Actual end point temperature versus estimated end point temperature for Model No.27

The metal droplets are produced due to the jet impact and the shearing action of the gas flow from the impact region when the jet strikes the metal surface and the product gases are deflected upwards.

The limiting diameter of the droplets (i.e. largest diameter droplets,  $d_{\text{limit}}$ ) is a function of the pressure at which oxygen is blown, lance height, lance inclination and nozzle diameter. Consider a 300 ton converter for which

$$\text{Flow rate of oxygen } (F_{\text{O}_2}) = 915 \text{ m}^3/\text{min, STP}$$

$$\text{Stagnant Pressure } P_0 = 10.2 \text{ atm}$$

$$\text{Throat dia } d_t = 46.6 \text{ mm}$$

$$\text{Exit pressure } P_e = 1.0 \text{ atm}$$

$$\text{Exit dia } d_e = 58.0 \text{ mm}$$

$$\text{Nozzle angle } \theta_t = 12^\circ$$

$$\text{No. of nozzles } n = 5$$

$$T_{\text{bulk}} = 1973 \text{ K}$$

$$T_{\text{hot spot}} = 2200 \text{ K}$$

$$\text{Lance height } = x = 2 \text{ m}$$

The expression to calculate  $d_{\text{limit}}$  is given by [12]

$$\begin{aligned} d_{\text{limit}} &= 5.513 \times 10^{-3} \left[ 10^6 \left( \frac{d_t}{x} \right)^2 P_a \left\{ 1.27 \left( \frac{P_0}{P_a} \right) - 1 \right\} \cos \theta \right]^{1.206} \text{ mm} \\ &= 5.513 \times 10^{-3} \left[ 10^6 \left( \frac{0.0466}{x} \right)^2 \times 1 \times \left\{ 1.27 \left( \frac{10.2 \times 1}{1} \right) - 1 \right\} \cos(12) \right]^{1.206} \quad (3.16) \\ &= \frac{1130.95}{x^{2.412}} \text{ mm} \end{aligned}$$

At a lance height of 2 m ( $x = 2$ ),  $d_{\text{limit}} = 212.5 \text{ mm}$  (or = 21.25 cm)

$$\text{Average diameter of droplets is given by [12] } (d_{\text{avg}}) = 0.2 d_{\text{limit}} \quad (3.17)$$

$$= 0.2 (21.25) = 4.25 \text{ cm}$$



Thus average radius of a droplet =  $4.25/2 = 2.125$  cm

If diffusion coefficient of carbon is  $3.24 \times 10^{-3}$  cm<sup>2</sup>/sec then from Eq. (2.6) the mass transfer coefficient  $k_c$  can be calculated as

$$k_c = 5D/a = 5 \times 3.24 \times 10^{-3} / (2.125) \\ = 7.623 \times 10^{-5} \text{ m/sec}$$

From Eq (2.5) the decarburization rate is

$$\frac{-d[C]}{dt} = k_c \frac{A}{V} [C]$$

On integrating the above equation, we obtain

$$-\ln\left(\frac{C_t - C_e}{C_{SL} - C_e}\right) = k_c \frac{A}{V} t \left(\frac{C_{SL}}{C_{SL} - C_e}\right) \quad (3.18)$$

where  $A$  = surface area

$V$  = volume

If the equilibrium carbon concentration ' $C_e$ ' is assumed to be very small then the equation (3.18) becomes

$$-\ln\left(\frac{C_t}{C_{SL}}\right) = k_c \frac{A}{V} t \quad (3.19)$$

$$\text{where } \frac{A}{V} = \frac{4\pi r^2}{(4/3)\pi r^3} = \frac{3}{r} = \frac{3}{2.125} = 1.4117 \text{ cm}^{-1} \\ = 141.17 \text{ m}^{-1}$$

From Eq (3.19) the time required to decrease the carbon concentration from 0.3% to 0.04% can be calculated as

$$-\ln (0.04 / 0.3) = 7.623 \times 10^{-5} \times 141.17 \times t$$

$$\text{Or } t = 187 \text{ sec.}$$

According to the procedure suggested in [12], iron conversion (i.e., total mass of iron droplets ejected from impact zone (tons/min) ) can be calculated as follows.

The dynamic impact pressure ( $P_{d,x}$ ) at the jet impact is given by an empirical relation[12].

$$\frac{P_{d,x}}{P_o} = 230 \left( \frac{x}{dt} \right)^{-2.4} \quad (3.20)$$

where,

$$P_{d,x} = P_o - P_v$$

$x$  = distance from nozzle exit

The functional relationship between iron conversion and Weber number (We) is [12]

$$Mg = f(We) \quad (3.21)$$

where the Weber number is defined as

$$We = \frac{\rho_g \cdot u_{o,x}^2}{(\rho_l g \sigma_l)^{1/2}} = \frac{2P_{d,x}}{(\rho_l g \sigma_l)^{1/2}} \quad (3.22)$$

where,

$\rho_l$  = density of liquid bath (7000 kg/m<sup>3</sup>)

$\rho_g$  = density of gas

$\sigma_l$  = surface tension of liquid (1.7 N/m)

$P_{d,x}$  =  $P_0 - P_v$

$u_{0,x}$  = center line velocity of gas at distance x from nozzle tip

In order to apply Eq(3.6) to a real system, the droplet generation per unit volume of blown gas must be considered. The plot of  $Mg/F_{O_2}$  versus Weber number is shown in Fig. (16). Using this graph, the best fit polynomial has been obtained as follows:

$$Mg/F_{O_2} = 9.862 - 0.8816 \times (We) + 0.02368 (We)^2 - 0.1415 \times 10^{-3} (We)^3 + 0.1572 \times 10^{-6} (We)^4 + 0.5402 \times 10^{-9} (We)^5 \quad (3.23)$$

On substituting Eq (3.20) in Eq (3.22), we get

$$We = \frac{2.0 \times 230 x P_0}{(\rho_l g \sigma_l)} \left( \frac{x}{dt} \right)^{-2.4} \quad (3.24)$$

since  $x = 2$  m,  $g = 9.81$  m/s<sup>2</sup>,  $P_0 = 10.2$  atm,  $dt = 0.0466$  m,  $\rho_l = 7000$  kg/m<sup>3</sup>,  $\sigma_l = 1.7$  N/m

we get  $We = 167.88$

Substituting this value in Eq. (3.23)

$$Mg/F_{O_2} = 56.65 \text{ kg/m}^3$$

Or  $Mg = 56.65 \times 915 \text{ m}^3/\text{min} = 51832 \text{ kg/min}$

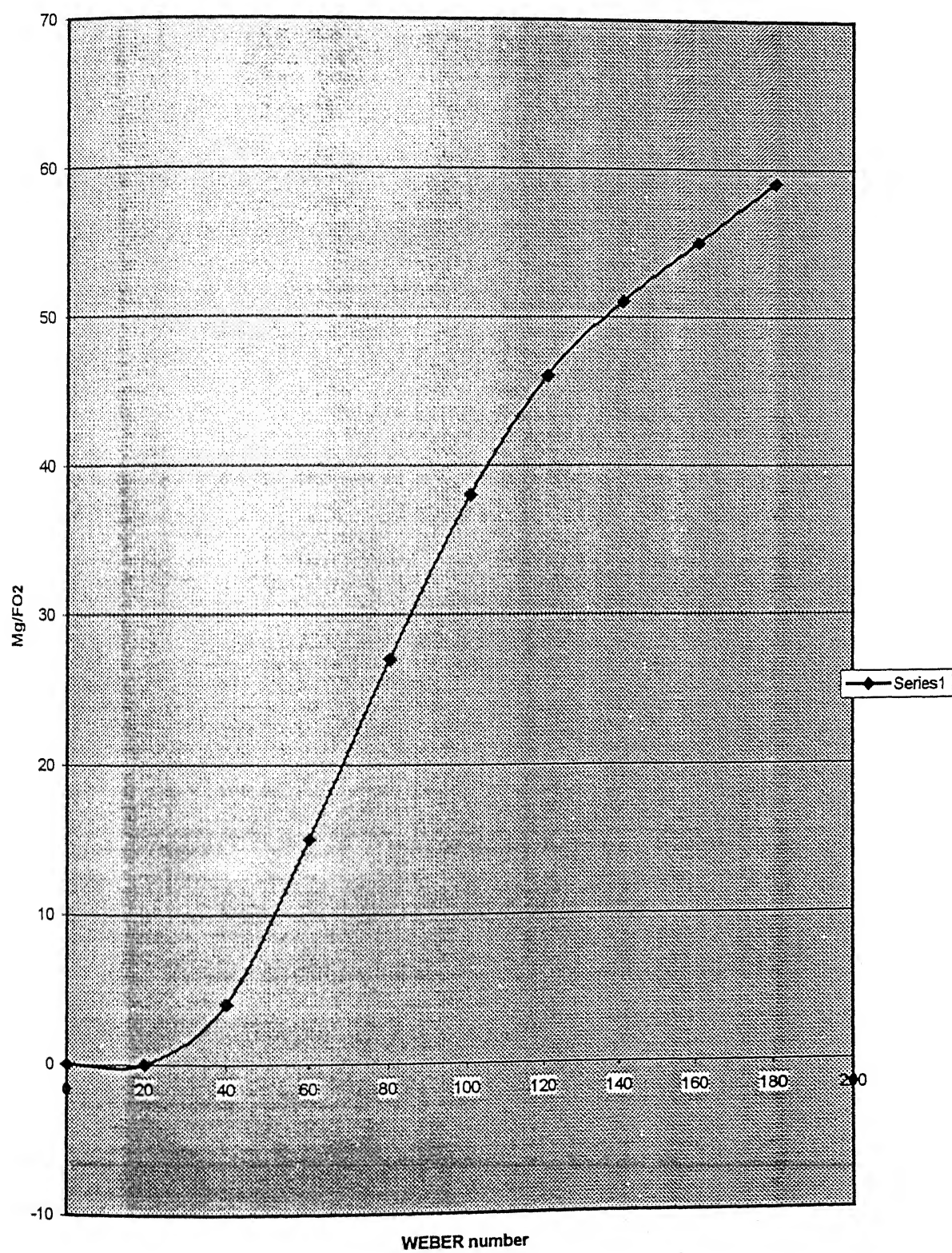


Fig. 16 Specific Iron conversion versus Weber number

$$= 51.832 \text{ ton/min (or } \approx 50 \text{ tons/min)}$$

Thus, the mass of droplets continuously circulated through slag during decarburization period is approximately 50 tons/min and only this metal would be subjected to decarburization via droplets (i.e. approximately one sixth of total metal). Additional decarburization can be conceived to occur either by assuming an enhanced mass transfer coefficient (by a factor of 6) within the droplet and/or decarburization at the interface of bulk metal and slag, and/or decarburization in the impact zone due to high recirculation rate of metal in the zone.

As far as bulk metal decarburization is concerned, the nominal area of metal bath for a 300 ton converter is approximately  $30 \text{ m}^2$ . Thus

$$\frac{A}{V} = \frac{30}{\left(\frac{300 \times 1000}{7000}\right)} = 0.7 \text{ m}^{-1}$$

The value of  $(A/V)$  for droplet is  $141.17 \text{ m}^{-1}$  where as  $(A/V)$  for bulk metal is 0.7, which is lower approximately by a factor of 200. It shows that the contribution of decarburization at the interface of bulk metal and slag is expected to be very small.

The diameter of jet impact zone is approximately 1 m. For a lance tip with 5 nozzles, the total area of impact will be  $5 \times \pi \times (0.5)^2 = 3.92 \text{ m}^2$ . Suppose that entire volume of metal is recirculated then  $V = 42.88 \text{ m}^3$ . Now for Model No.4 the value of capacity coefficient of mass transfer is approximately  $0.1 \text{ s}^{-1}$ . Hence mass transfer coefficient can be computed as

$$K = k_c \cdot \frac{A}{V}$$

$$\text{Or } k_c = K \cdot \frac{V}{A} = 0.1 \times \frac{42.98}{3.92} \text{ m/s}$$

$$= 1.09 \text{ m/s}$$

Since mass transfer coefficient is directly proportional to fluid velocity, the average recirculation velocity of metal is of the order of 1 m/s. Such a magnitude has been predicted from fluid flow computations in the impact zone[12] . It therefore indicates that most of decarburization can occur in impact zone.

### 3.3.2 Comparative evaluation of models for carbon and temperature

Various alternatives were tried to predict end point carbon, Models 1-10, on the same data set (see Table 1 for summary of results ). The adequacy of models has been compared on the basis of standard deviation in Fig (17). It can be seen that in Models 1-10, the standard deviation has gradually decreased to approximately 8 milli percent. The independent variables finally selected for regression are time, lance height, ore (added as coolant after sublimation measurement) and basicity of slag. From theoretical view point, all these variables do affect decarburization process. For example, lance height influences recirculation rate of metal, basicity of slag lying on top of metal also influences recirculation rate and residence time of droplets in slag and ore added directly supplies additional oxygen for decarburization. The respective signs of coefficients in Model No. 10 are also correct, positive for time, negative for lance height, positive for ore and negative for basicity. If average values of each of these variables is considered (time = 200 sec, lance height =2 m, ore added =300 kg, and basicity =3 ), then it would be seen for Model No. 10 that contribution of time = 1.72,

contribution of lance height=-0.015, contribution of ore =0.038 and contribution of basicity =-0.156. It shows that most important variables in converter operation is time, followed by basicity, ore and lance height.

Comparative performance of carbon models of different plants (in terms of standard deviation of carbon) is shown in Fig (18) and the best performance is obtained for plant 2.

Comparison of the performance of different temperature models (Model No. 15-24 summarized in Table (1)) is shown in Fig (19). The best results are obtained for Model No.15 ( $\sigma = \pm 4.986$  °C) and Model No. 17 ( $\sigma = \pm 4.986$  °C) for data set1. The performance of same model when same variables applied to the data of different plants is compared in Fig (20); best results are obtained for plant 1.

The variables selected in Model No.15 and Model No.17 are time (oxygen blown), lance life, temperature at subblance point, second blow additions, ore added (coolant), ratios of hot metal and scrap, end point carbon and basicity. From physical considerations also, all these variables are expected to affect bath temperature. Individual differences in the performance of models for different plants reflects upon the particular situation existing in a plant.

To summarize :

- the best model for carbon prediction for plant 1 is Model No.(10),  $\sigma = \pm 7.4204$  milli %.
- the best model for carbon prediction for plant 2 is Model No.(11),  $\sigma = \pm 6.8061$  milli %.
- the best model for carbon prediction for plant 3 is Model No.(12),  $\sigma = \pm 7.6765$  milli %.
- the best model for carbon prediction for plant 4 is Model No.(13),  $\sigma = \pm 8.0459$  milli %

- the best model for temperature prediction for plant 1 is Model No.(17),  $\sigma = \pm 4.986$  °C
- the best model for temperature prediction for plant 2 is Model No.(24),  $\sigma = \pm 5.518$  °C
- the best model for temperature prediction for plant 3 is Model No.(25),  $\sigma = \pm 6.1215$  °C
- the best model for temperature prediction for plant 4 is Model No.(27),  $\sigma = \pm 8.2032$  °C

It may be noted that Model Nos. (9), (11), (12) and (14) for carbon prediction have been developed in the present work. These results show that carbon oxidation essentially occurs in the recirculation zone just below the jet. The best model for temperature prediction is a modified form of the model proposed by Bessho et al. and Byun et al.



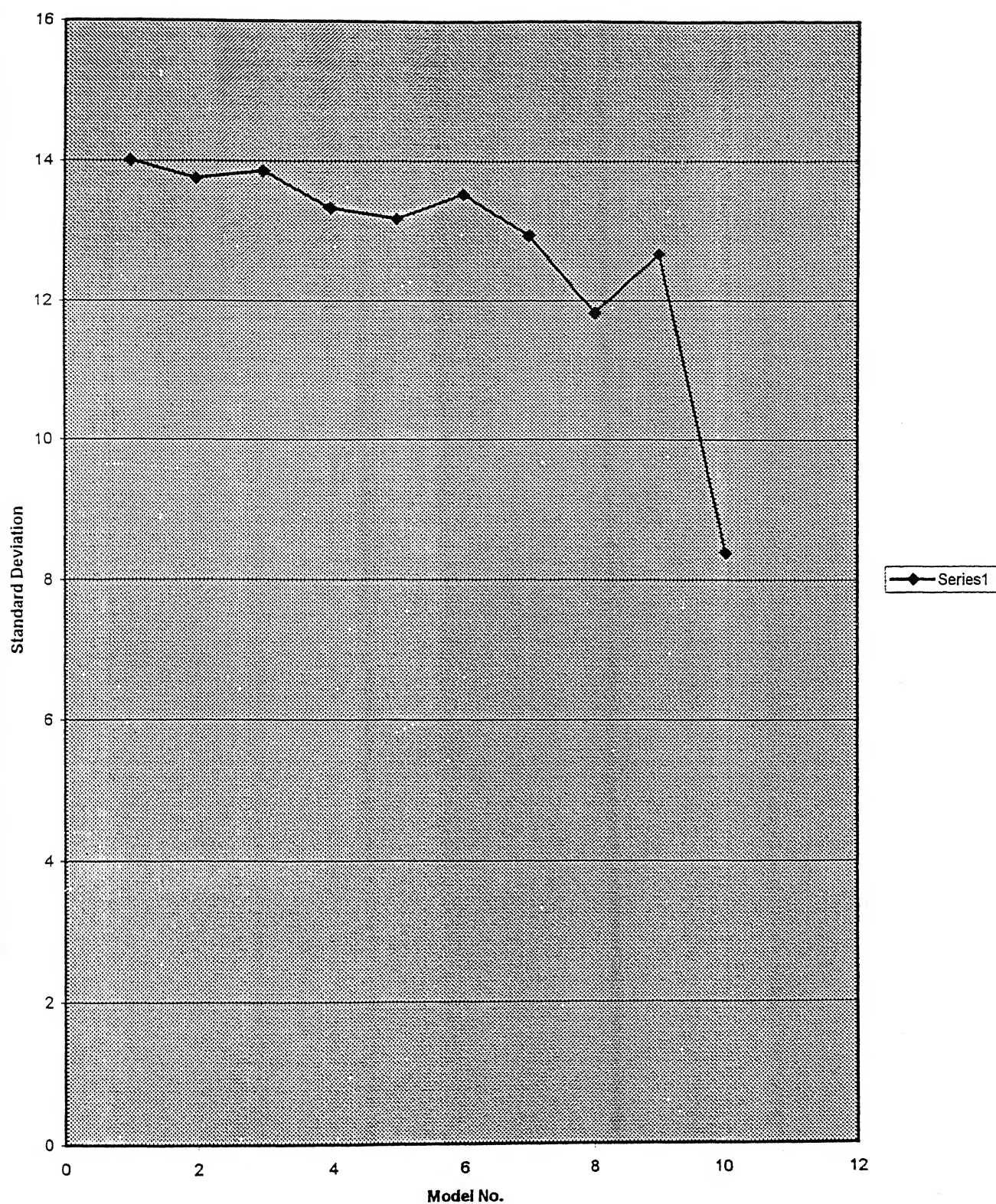


Fig. 17. Comparative performance of different carbon models (Model Nos. 1-10) of plant (1)

Data set (compared values of  $y=mx$  curve, before  $\pm 2\sigma$ )

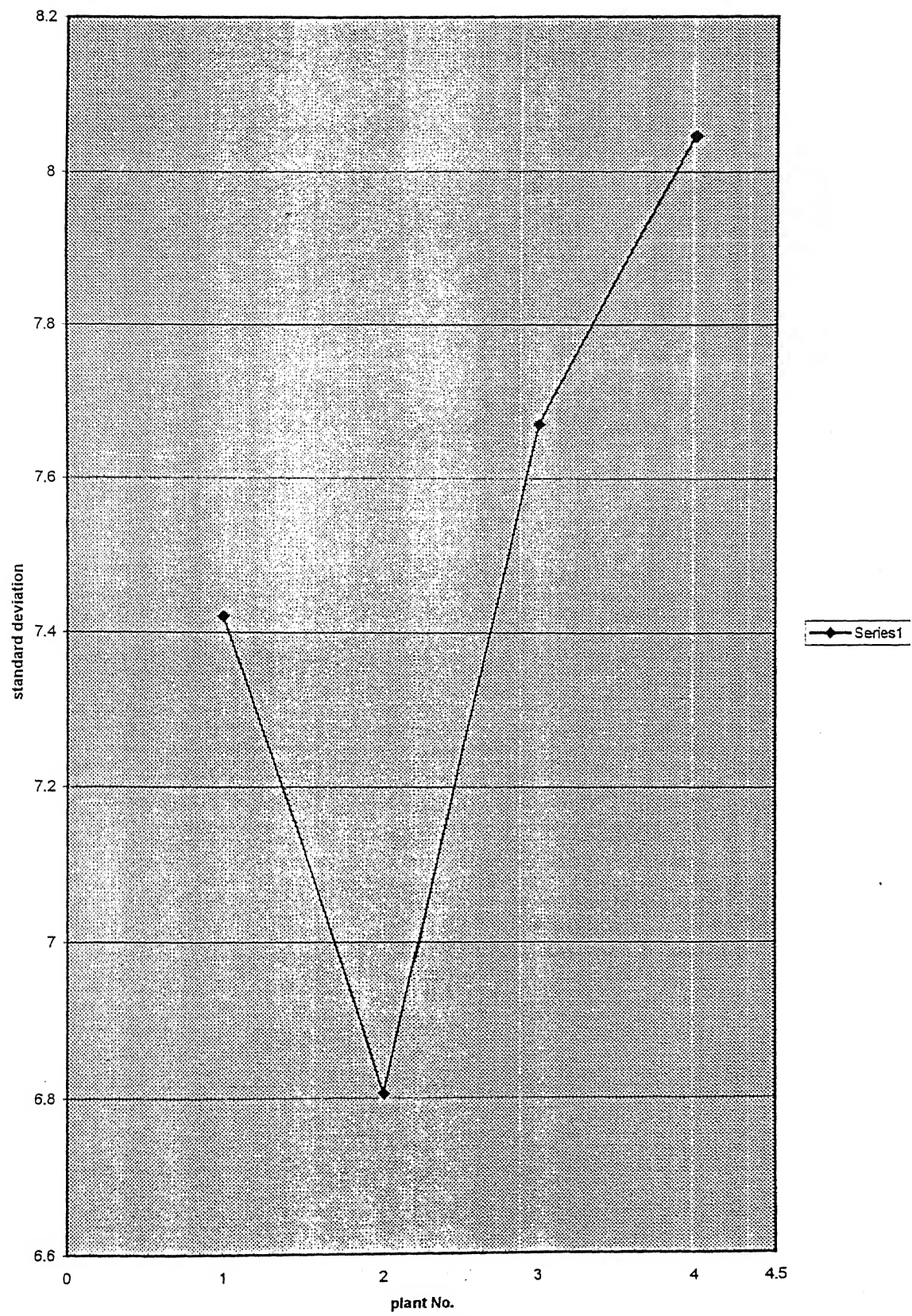


Fig. 18. Comparative performance of carbon models of different plants (compared values of  $y=mx+c$ , after  $\pm 2 \sigma$ )

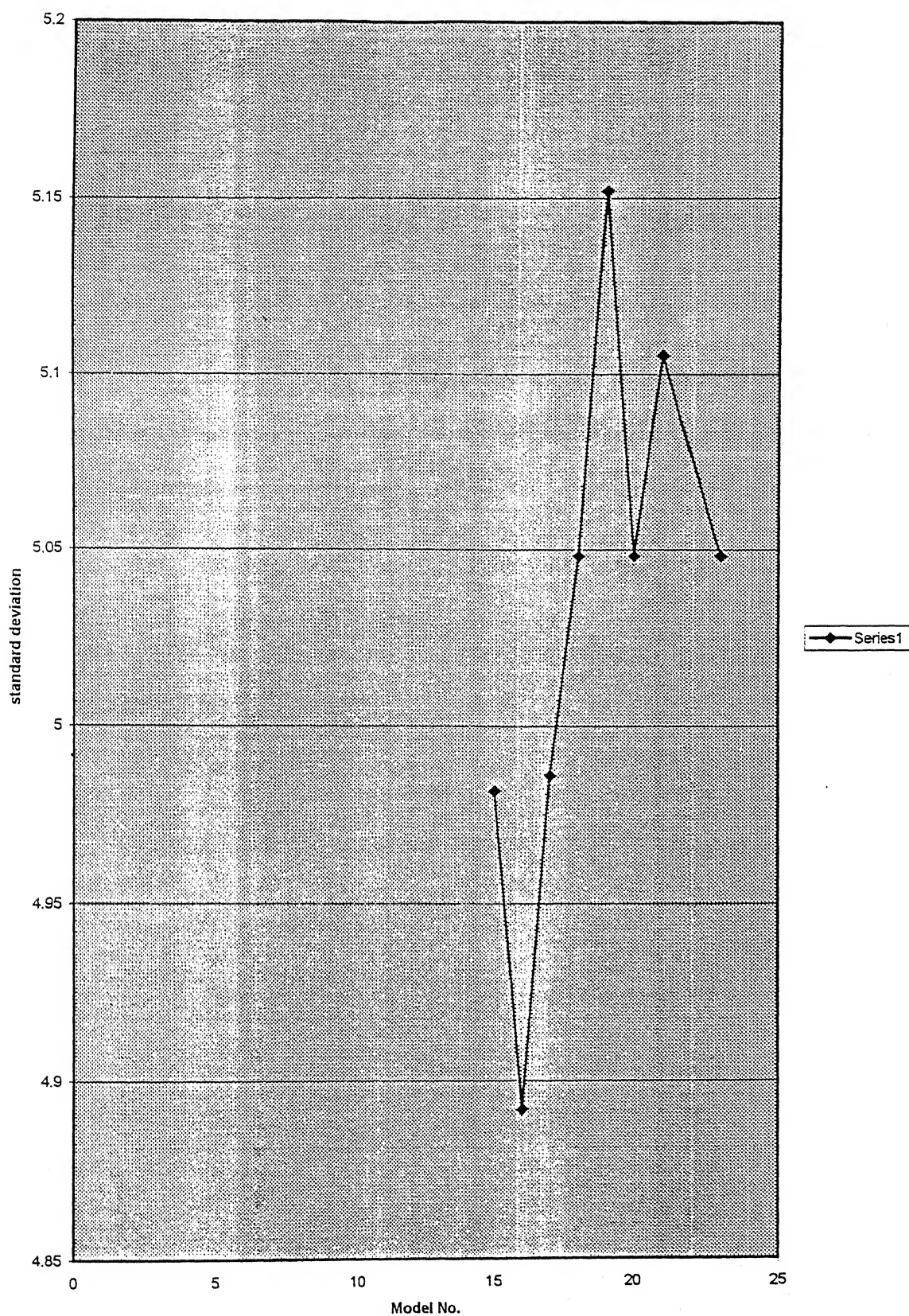


Fig. 19. Comparative performance of different temperature models(Model Nos.15-23) of paint (1) Data set (compared values of  $y=mx+c$  curve, after  $\pm 2\sigma$ )



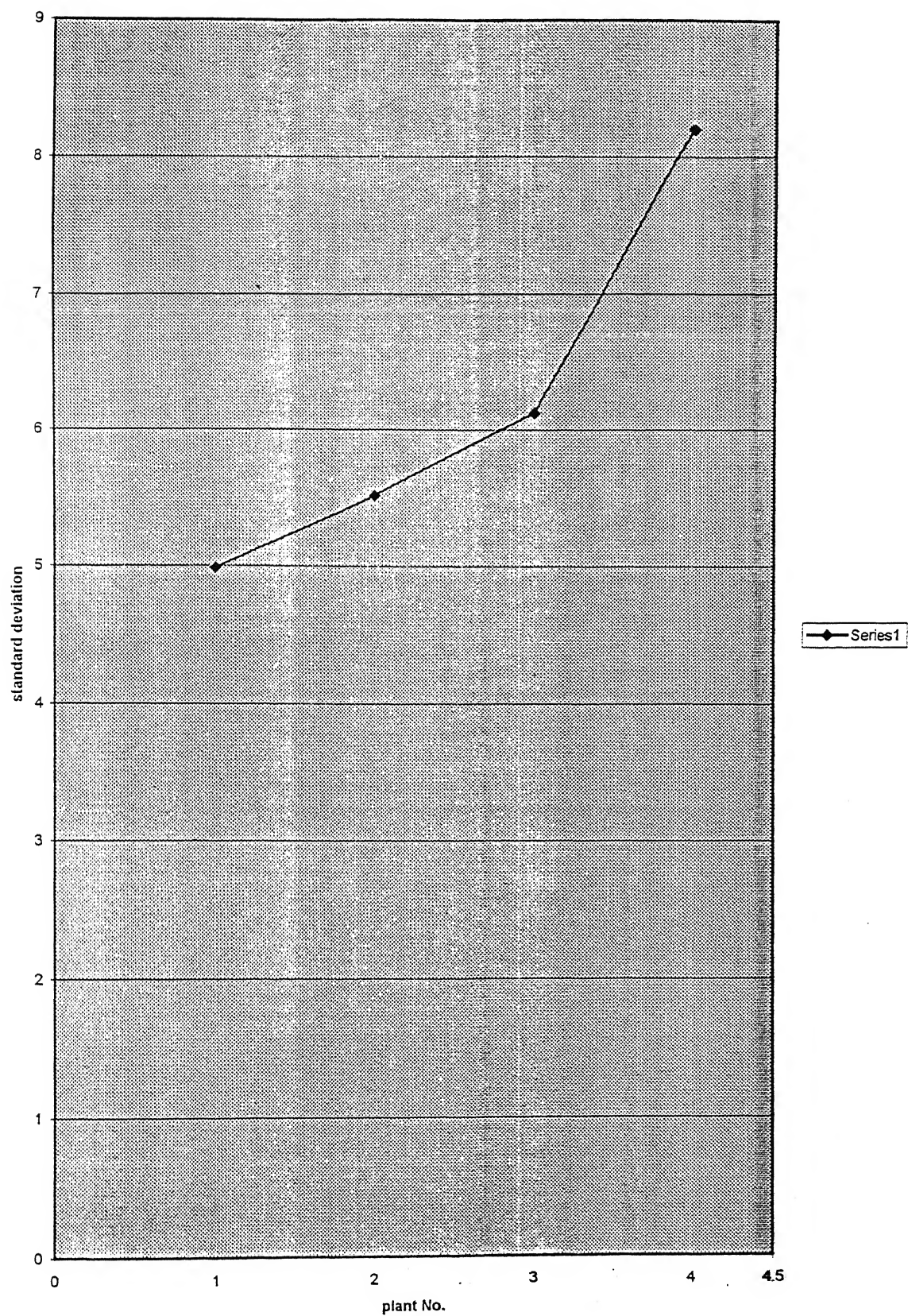


Fig. 20. Comparative performance of temperature models of different plants (compared values of  $y=mx+c$ , after  $\pm 2\sigma$ )

## CHAPTER 4

### CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

#### 4.0 Conclusions

(1). The models developed in the present work for prediction of end point carbon and temperature give better predictions as compared to the exponential model and other models reported in the literature. It is found that decarburization occurs primarily in recirculation zone in and around the area of jet impingement.

(2). Lowest possible standard deviations and highest correlation coefficients, obtained at four different plants for the end point carbon prediction are

		Variables selected are
Plant (1)	$\sigma = \pm 7.4204$	time (0.0086379)
	$R = 0.7728$	lance height (-0.0076609)
	(for Model No. 10)	ore added (0.0001127)
		basicity (-0.0526011)
		Constant (2.268365)

Equation for prediction of  $C_f = C_e + (C_{st} - C_e) \cdot \exp\{-[ \text{Constant} + \text{time} (0.0086379) + \text{lance height} (-0.0076609) + \text{ore added} (0.0001127) + \text{basicity} (-0.0526011)]\}$

Plant (2)	$\sigma = \pm 6.8061$	time (0.008465324)
	$R = 0.6509$	ore added (0.000019422)
	(for Model No.11)	basicity (-0.024093316)
		Constant (0.490082)

Equation for prediction of  $C_r = C_e + (C_{sl} - C_e) \cdot \exp\{-[ \text{Constant} + \text{time (0.008465324)} + \text{ore added (0.000019422)} + \text{basicity (-0.024093316)} ]\}$

Plant (3)	$\sigma = \pm 7.6705$	time (0.012579485)
	$R = 0.6631$	ore added (0.000104090)
	(for Model No.12)	basicity (-0.035449106)
		Constant (0.403394)

Equation for prediction of  $C_r = C_e + (C_{sl} - C_e) \cdot \exp\{-[ \text{Constant} + \text{time (0.012579485)} + \text{ore added (0.000104090)} + \text{basicity (-0.035449106)} ]\}$

Plant (4)	$\sigma = \pm 8.0459$	time (0.008016913)
	$R = 0.6472$	ore added (0.00003738)
	(for Model No.13)	hot ratio (0.008102343)
		dolomite (-0.000112685)
		Constant (1.122772)

Equation for prediction of  $C_r = C_e + (C_{sl} - C_e) \cdot \exp\{-[ \text{Constant} + \text{time (0.008016913)} + \text{ore added (0.00003738)} + \text{hot ratio (0.008102343)} + \text{dolomite (-0.000112685)} ]\}$

(3). Lowest possible standard deviation and highest correlation coefficients, obtained for temperature prediction in the four plants are

		Variables selected are
Plant (1)	$\sigma = \pm 4.986$	lance life (0.0230456)
	$R = 0.8458$	temperature at sublance
		(0.6939638)
	(for Model No.15)	ore added (-0.0093125)
		basicity (0.291021)
		second blow additions
		(-0.0030052)
		hot ratio (1.2891021)
		$\Delta O_2$ (7.436825)
		$(1/C_f - 1/C_{SL})$ (0.7156683)
		Constant (493.773952)

Equation for prediction of  $T_r = \text{Constant} + \text{lance life (0.0230456)} + \text{temperature at sublance (0.6939638)} + \text{ore added (-0.0093125)} + \text{basicity (0.291021)} + \text{second blow additions (-0.0030052)} + \text{hot ratio (1.2891021)} + \Delta O_2 (7.436825) + (1/C_f - 1/C_{SL}) (0.7156683)$

Plant (2)	$\sigma = \pm 5.518$	temperature at sublance
	$R = 0.8785$	(0.86734136)
	(for Model No.24)	ore added (-0.006905308)
		second blow additions

(-0.008240974)

oxygen blown

(0.036247155)

Constant (210.817727 )

Equation for prediction of  $T_f$  = Constant + temperature at subblance (0.86734136) + ore added  
 (-0.006905308) + second blow additions (-0.008240974) +  
 oxygen blown (0.036247155)

Plant (3)

$\sigma = \pm 6.1215$

temperature at subblance

$R = 0.8712$

(0.849737782)

(for Model No.25)

ore added (-0.004436813)

second blow additions

(-0.007871726)

oxygen blown

(0.037140187)

Constant (234.027158)

Equation for prediction of  $T_f$  = Constant + temperature at subblance (0.849737782) + ore added  
 (-0.004436813) + second blow additions (-0.007871726) +  
 oxygen blown (0.037140187)

Plant (4)

$\sigma = \pm 8.2032$

temperature at subblance

$R = 0.8575$

(0.881824165)

(for Model No.27)

ore added (-0.010025682)



lime(-0.000257262)

dolomite (-0.02135692)

$\Delta O_2$  (12.078419703)

$(C_{SL} - C_F)$  (-0.040002643)

Constant =221.672589

Equation for prediction of  $T_F$  =Constant + temperature at substance (0.881824165) +ore added  
 (-0.010025682) +lime (-0.000257262)+dolomite (-0.02135692)  
 +  $\Delta O_2$  (12.078419703) +  $(C_F - C_{SL})$ (-0.040002643)

(4). Both lance height and lance life are important variables and if data on these are made available then carbon prediction can be improved by nearly 0.8 milli percent and temperature prediction by 0.8 °C.

(5). Slag basicity is a more significant variable than slag volume. The former determines the viscosity and hence foaming characteristics of slag.

(6). Slightly better prediction of temperature and carbon can be obtained in converter equipped with bottom stirring (plants 1,2 and 3 ) than otherwise (plant 4).

## 4.1 Suggestions for Further work

(1). The models developed in the present work need to be extended to the prediction of end point manganese and phosphorus as well. Preliminary work has already shown that phosphorus can be predicted in the range of  $\sigma = \pm 1.6$  milli percent and manganese in the range of  $\sigma = \pm 5$  milli percent.

(2). Specific influences of lance height and nozzle design on process kinetics need to be studied in detail.

(3). The models obtained in the present work can be further tuned by using soft computing techniques including neural nets, genetic algorithms and fuzzy logic.

Table. (1) Summary of results of models for carbon and temperature prediction

Model No.	Dependent variable in regression	Independent variables taken in regression	Selected variables by stepwise regression and corresponding coefficients	For the regression curve	Before $\pm 2\sigma$	After $\pm 2\sigma$
			Results for Exponential model (plant (1) data set)			
1	$C_p$	temperature at subblance, second blow additions, slag volume, ore added, hotratio.	ore added(-0.0000532), hotratio(0.0187208), Regression constant (0.484089).	$y=mx$	n=301 m=0.98933 $\sigma = 14.002$ R=0.66119 F=6865	n=284 m=1.00528 $\sigma = 11.4872$ R=0.73016 F=9404
				$y=mx+c$	n=301 m=0.5981 c=27.3968 $\sigma = 12.0415$ R=0.6612 F=232	n=285 m=0.5958 c=27.002 $\sigma = 10.1623$ R=0.71 F=287
2	$C_p$	lance height, temperature at subblance, second blow additions, slag volume, ore added, hotratio	lance height(-0.0002785), ore added(-0.0000572), hotratio(0.0185860), Regression constant (0.509299).	$y=mx$	n=301 m=0.98808 $\sigma = 13.7495$ R=0.66998 F=7102	n=292 m=0.99813 $\sigma = 12.1226$ R=0.71026 F=8724
				$y=mx+c$	n=301 m=0.5782 c=27.3066 $\sigma = 11.7602$ R=0.67 F=243	n=287 m=0.5809 c=28.0326 $\sigma = 9.9284$ R=0.7081 F=286
3	$C_p$	All the variables (temperature at subblance, second blow additions, slag volume, ore added, hotratio) less thier corresponding mean values.	(ore added-mean of ore added) (-0.0000532), (hotratio-mean of hotratio)(0.0187208), Regression constant(0.5556).	$y=mx$	n=301 m=0.96853 $\sigma = 13.8538$ R=0.66119 F=6865	n=286 m=0.95147 $\sigma = 11.2682$ R=0.7349 F=9373
				$y=mx+c$	n=301 m=0.7309 c=16.6945 $\sigma = 13.31$ R=0.6612 F=232	n=284 m=0.6916 c=17.6208 $\sigma = 10.3263$ R=0.7301 F=321
			Subblance model :Method 1 (for plant (1) data set )			
4	K	temperature at subblance, second blow additions, ore added, hotratio	ore added(0.000000635), basicity(-0.000215759), Regression constant (0.10422).	$y=mx$	n=301 m=0.9542 $\sigma = 13.33$ R=0.6627 F=7046	n=288 m=0.96759 $\sigma = 11.43$ R=0.7315 F=9130
5	K	lance height, temperature at subblance, second blow additions, ore added, hotratio	lance height(0.000003467), ore added(0.000000683), basicity(-0.000219421), Regression constant (0.010135).	$y=mx$	n=301 m=0.9539 $\sigma = 13.173$ R=0.6688 F=7211	

<sup>1</sup> n=number of data points, m=slope of curve, c=constant,  $\sigma$ =standard deviation, R=correlation coefficient, F=F-test value

(continued ...)

Summary of results of models for carbon and temperature prediction (continued ..)

10	$-\ln \frac{C_i - C_s}{C_{SL} - C_s}$	time,lance height, temperature at sub lance,second blow additions, ore added, hot ratio,basicity	time(0.0086379), lance height(-0.0076609), ore added(0.0001127), basicity(-0.0526011), Regression constant (2.268365).	y=mx	n=272 m=0.94839 $\sigma$ =11.61 R=0.74384 F=8341	n=263 m=0.96813 $\sigma$ =10.0727 R=0.78413 F=10739
				y=mx+c	n=272 m=0.5170 c=30.3324 $\sigma$ =8.3772 R=0.7438 F=334	n=262 m=0.5284 c=29.3979 $\sigma$ =7.4204 R=0.7728 F=385
			Modified method (2) (for plant (2) data set )			
11	$-\ln \frac{C_i - C_s}{C_{SL} - C_s}$	time,temperature at sub lance, second blow additions, ore added, hot ratio,basicity	time(0.008465324), ore added(0.000019422), basicity(-0.024093316), Regression constant (0.490082).	y=mx	n=1744 m=0.96204 $\sigma$ =10.2214 R=0.6341 F=53258	n=1667 m=0.98114 $\sigma$ =8.7025 R=0.6642 F=69818
				y=mx+c	n=1744 m=0.4664 c=29.9053 $\sigma$ =7.6145 R=0.6341 F=1171	n=1671 m=0.4545 c=30.5902 $\sigma$ =6.8061 R=0.6509 F=1227
			Modified method (2) (for plant (3) data set )			
12	$-\ln \frac{C_i - C_s}{C_{SL} - C_s}$	time,temperature at sub lance, second blow additions, ore added, hot ratio,basicity	time(0.012579485), ore added(0.000104090), basicity(-0.035449106), Regression constant (0.403394).	y=mx	n=748 m=0.9491 $\sigma$ =12.2767 R=0.61921 F=16771	n=715 m=0.97358 $\sigma$ =10.0979 R=0.63631 F=23409
				y=mx+c	n=748 m=0.4343 c=32.6684 $\sigma$ =8.8244 R=0.6192 F=463	n=711 m=0.4329 c=32.4388 $\sigma$ =7.6765 R=0.6631 F=556

<sup>1</sup> n=number of data points, m=slope of curve, c=constant,  $\sigma$ =standard deviation, R=correlation coefficient, F=F-test value

(continued ...)

Summary of results of models for carbon and temperature prediction (continued ...)

6	K	lance height, temperature at sublance, second blow additions, slag volume, ore added, hot ratio	lance height (0.000003288), ore added(0.000000764), Regression constant (0.009085).	y=mx	n=301 m=0.95329 $\sigma$ =13.522 R=0.6497 F=6834	
			Sublance model: Method 2 (for plant (I) data set )			
7	$-\ln \frac{C_t}{C_{SL}}$	time, temperature at sublance, second blow additions, ore added, hot ratio, basicity	time(0.007827967), ore added(0.000114356), basicity(-0.040036131), Regression constant (0.473776).	y=mx	n=301 m=0.95311 $\sigma$ = 12.9347 R=0.66582 F=7466	n=289 m=0.97334 $\sigma$ = 11.027 R=0.73165 F=9867
				y=mx+c	n=301 m=0.496 c=32.0314 $\sigma$ = 8.615 R=0.6658 F=238	n=282 m=0.497 c=31.4141 $\sigma$ = 8.3363 R=0.7138 F=290
8	$-\ln \frac{C_t}{C_{SL}}$	time, lance height, temperature at sublance, second blow additions, ore added, hot ratio, basicity	time(0.0078753), lance height(-0.0066976), ore added(0.0001102), basicity(-0.0466949), Regression constant (2.013246).	y=mx	n=301 m=0.95856 $\sigma$ =11.816 R=0.73992 F=8226	n=261 m=0.98009 $\sigma$ =10.012 R=0.79227 F=11022
				y=mx+c	n=272 m=0.5692 c=27.3729 $\sigma$ = 9.333 R=0.7399 F=326	n=259 m=0.5977 c=25.5638 $\sigma$ = 8.092 R=0.7784 F=395
			Modified method 2 (for plant (I) data set )			
9	$-\ln \frac{C_t - C_e}{C_{SL} - C_e}$	time, temperature at sublance, second blow additions, ore added, hot ratio, basicity	time(0.008554170), ore added(0.000118546), basicity(-0.04342846), Regression constant (0.505659).	y=mx	n=301 m=0.94268 $\sigma$ =12.6652 R=0.66826 F=7618	n=286 m=0.96702 $\sigma$ =10.5013 R=0.73212 F=10511
				y=mx+c	n=301 m=0.4428 c=35.0092 $\sigma$ =8.7458 R=0.6683 F=241	n=286 m=0.45 c=34.1851 $\sigma$ =7.613 R=0.712 F=291

(continued ...)

<sup>1</sup> n=number of data points, m=slope of curve, c=constant,  $\sigma$ =standard deviation, R=correlation coefficient, F=F-test value

Summary of results of models for carbon and temperature prediction (continued ..)

			Modified method (2) (for plant (4) data set )			
13	$-\ln \frac{C_t - C_e}{C_{SL} - C_e}$	time,temperature at subblance, hot ratio,ore added,basicity, dolomite (end point carbon<0.06)	time(0.008016913), ore added(0.00003748), hotratio(0.008102343), dolomite(-0.000112685), regression constant (1.122772).	y=mx	n=1832 m=1.01352 $\sigma$ =9.5153 R=0.58892 F=32216	n=1742 m=1.01989 $\sigma$ =8.1368 R=0.6739 F=44316
				y=mx+c	n=1832 m=0.7518 c=10.8853 $\sigma$ =9.2116 R=0.5889 F=971	n=1755 m=0.772 c=10.0659 $\sigma$ =8.0459 R=0.6472 F=1263
14	$-\ln \frac{C_t - C_e}{C_{SL} - C_e}$	time,temperature at subblance, ore added, hot ratio,basicity, (lime+dolomite)	time(0.008269546), basicity(0.024547185), (lime+dolomite) (-0.000011592), hotratio(0.007897235), Regression constant (0.990858).	y=mx	n=1832 m=1.0201 $\sigma$ =9.475 R=0.61437 F=34958	n=1750 m=1.02497 $\sigma$ =8.1837 R=0.69078 F=44558
				y=mx+c	n=1832 m=0.8092 c=8.7710 $\sigma$ =9.279 R=0.6144 F=1109	n=1758 m=0.8233 c=8.1164 $\sigma$ =8.1364 R=0.667 F=1407
			Temperature model (for plant (1) data set )			
15	End point temperature	lance life, temperature at subblance,second blow additions, ore added, hot ratio,basicity, $\Delta O_2$ (1/C <sub>t</sub> -1/C <sub>SL</sub> )	lance life(0.0230456), temperature at subblance(0.6939638), second blow additions (-0.0030052), ore added(-0.0093125), hot ratio(1.2891021), $\Delta O_2$ (7.436825), (1/C <sub>t</sub> -1/C <sub>SL</sub> )(0.7156683), basicity(0.291021), regression constant (493.773952).	y=mx	n=301 m=0.99998 $\sigma$ =7.4481 R=0.79888 F=15068846	n=284 m=0.99969 $\sigma$ =6.1355 R=0.857 F=20943815
				y=mx+c	n=301 m=0.63816 c=602.99247 $\sigma$ =5.9596 R=0.79888 F=527	n=287 m=0.6442 c=592.4415 $\sigma$ =4.986 R=0.8458 F=716
16	End point temperature	lance height, temperature at subblance,second blow additions, ore added, hot ratio,slag volume, $\Delta O_2$ (1/C <sub>t</sub> -1/C <sub>SL</sub> )	temperature at subblance(0.7082811), second blow additions (-0.0039811), ore added(-0.0087737), $\Delta O_2$ (7.7104538), (1/C <sub>t</sub> -1/C <sub>SL</sub> )(0.7461434), regression constant (477.550594).	y=mx	n=301 m=0.9998 $\sigma$ =7.6108 R=0.79407 F=13037529	n=256 m=0.9997 $\sigma$ =6.1632 R=0.85716 F=18704929
				y=mx+c	n=301 m=0.63054 c=615.6147 $\sigma$ =6.0546 R=0.79407 F=460	n=258 m=0.6250 c=624 $\sigma$ =4.8919 R=0.8458 F=643

n=number of data points, m=slope of curve, c=constant,  $\sigma$ =standard deviation, R= correlation coefficient, F=F-test value

(continued ...)

Summary of results of models for carbon and temperature prediction (continued ...)

17	End point temperature	lance height, lance life, temperature at subblance, second blow additions, ore added, hot ratio, basicity, $\Delta O_2$ ( $1/C_r - 1/C_{sl}$ )	lance life(0.0230456), temperature at subblance(0.6939638), second blow additions (-0.0030052), ore added(-0.0093125), hot ratio(1.2891021), $\Delta O_2$ (7.436825), ( $1/C_r - 1/C_{sl}$ )(0.7156683), basicity(0.291021), regression constant (493.773952).	y=mx	n=301 m=0.99998 $\sigma$ =7.4481 R=0.79888 F=15068846	n=284 m=0.99969 $\sigma$ =6.1355 R=0.857 F=20943815
				y=mx+c	n=301 m=0.63816 c=602.99247 $\sigma$ =5.9596 R=0.79888 F=527	n=287 m=0.6442 c=592.4415 $\sigma$ =4.986 R=0.8458 F=716
18	End point temperature	lance height, lance life, temperature at subblance, second blow additions, ore added, hot ratio, basicity, $\Delta O_2$ ( $1/C_{sl}$ )	lance life(0.0246530), temperature at subblance(0.7115224), second blow additions (-0.0037345), ore added(-0.0086561), $\Delta O_2$ (9.2189470), regression constant (471.875508).	y=mx	n=301 m=0.99998 $\sigma$ =7.911 R=0.76931 F=13356695	n=285 m=0.99966 $\sigma$ =6.68 R=0.82328 F=17727552
				y=mx+c	n=301 m=0.5918 c=680.2434 $\sigma$ =6.0959 R=0.7693 F=433	n=284 m=0.5990 c=667.7823 $\sigma$ =5.0482 R=0.8272 F=611
19	End point temperature	temperature at subblance, second blow additions, ore added, hot ratio, slag volume, $\Delta O_2$ ( $1/C_{sl}$ )	temperature at subblance(0.7131490), second blow additions (-0.0037001), ore added(-0.0090445), $\Delta O_2$ (9.3002569), regression constant (470.967881).	y=mx	n=301 m=0.99998 $\sigma$ =7.997 R=0.7635 F=13071322	n=285 m=0.99965 $\sigma$ =6.7517 R=0.82009 F=17601267
				y=mx+c	n=301 m=0.5829 c=695.0989 $\sigma$ =6.1 R=0.7635 F=417	n=287 m=0.5883 c=685.6120 $\sigma$ =5.152 R=0.8167 F=570
20	End point temperature	lance life, temperature at subblance, second blow additions, ore added, hot ratio, slag volume, $\Delta O_2$ ( $1/C_{sl}$ )	lance life(0.0246530), temperature at subblance(0.7115224), second blow additions (-0.0037345), ore added(-0.0086561), $\Delta O_2$ (9.2189470), regression constant (471.875508).	y=mx	n=301 m=0.99998 $\sigma$ =7.911 R=0.76931 F=13356695	n=285 m=0.99966 $\sigma$ =6.68 R=0.82328 F=17727552
				y=mx+c	n=301 m=0.5918 c=680.2434 $\sigma$ =6.0959 R=0.7693 F=433	n=284 m=0.5990 c=667.7823 $\sigma$ =5.0482 R=0.8272 F=611

n=number of data points, m=slope of curve, c=constant,  $\sigma$ =standard deviation, R=correlation coefficient, F=F-test value

(continued ...)

## Summary of results of models for carbon and temperature prediction (continued ..)

21	End point temperature	lance height, temperature at subblance, second blow additions, ore added, hot ratio, slag volume, $\Delta O_2$ ( $1/C_{sl}$ )	lance height(-0.1049593), temperature at subblance(0.7139081), second blow additions (-0.0045665), ore added(-0.008369), $\Delta O_2$ (9.3958176), regression constant (492.736455).	y=mx	n=301 m=0.9998 $\sigma$ =7.9949 R=0.76962 F=11814652	n=257 m=0.99964 $\sigma$ =6.6299 R=0.83180 F=16226661
				y=mx+c	n=301 m=0.59231 c =679.314 $\sigma$ =6.1645 R=0.76962 F=392	n=258 m=0.6084 c =651.8922 $\sigma$ =5.1054 R=0.8301 F=567
22	End point temperature	temperature at subblance, second blow additions, ore added, hot ratio, slag volume, oxygen flow rate, ( $1/C_{sl}$ )	temperature at subblance(0.6981714), second blow additions (-0.0033568), ore added(-0.0092944), hot ratio(1.6559167), oxygen flow rate (0.0276449), regression constant(488.152365)	y=mx	n=301 m=0.99998 $\sigma$ =8.0494 R=0.75989 F=12901493	
23	End point temperature	lance life, temperature at subblance, second blow additions, ore added, hot ratio, slag volume, $\Delta O_2$ ( $1/C_f - 1/C_{sl}$ ) [end point carbon calculated from carbon model No.(8)]	lance life(0.0246530), temperature at subblance(0.7115224), second blow additions (-0.0037345), ore added(-0.0086561), $\Delta O_2$ (9.2189470), regression constant (471.875508).	y=mx	n=301 m=0.99998 $\sigma$ =7.911 R=0.76931 F=13356695	n=285 m=0.99966 $\sigma$ =6.68 R=0.82328 F=17727552
				y=mx+c	n=301 m=0.5918 c=680.2434 $\sigma$ =6.0959 R=0.7693 F=433	n=284 m=0.5990 c=667.7823 $\sigma$ =5.0482 R=0.8272 F=611
			Temperature model (for plant (2) data det )			
24	End point temperature	temperature at subblance, second blow additions, ore added, hot ratio, slag volume, oxygen flow rate, ( $1/C_{sl}$ )	temperature at subblance(0.86734136), second blow additions (-0.008240974), ore added(-0.006905308), oxygen flow rate (0.036247155), regression constant (210.817727).	y=mx	n=1744 m=0.99998 $\sigma$ =7.5264 R=0.84834 F=86061195	n=1659 m=0.99996 $\sigma$ =6.5335 R=0.87849 F=108632432
				y=mx+c	n=1744 m=0.7197 c=468.7203 $\sigma$ =6.3866 R=0.8483 F=4472	n=1662 m=0.7129 c=480.0948 $\sigma$ =5.518 R=0.8785 F=5611

<sup>1</sup> n=number of data points, m=slope of curve, c=constant,  $\sigma$ =standard deviation, R=correlation coefficient, F=F-test value

(continued ...)



Summary of results of models for carbon and temperature prediction (continued ..)

25	End point temperature	temperature at subblance, second blow additions, ore added, hot ratio, slag volume, oxygen flow rate, $(1/C_{sl})$	Temperature model (for plant (3) data set ) temperature at subblance(0.819737782), second blow additions (-0.007871726), ore added(-0.004436813), oxygen flow rate (0.037140187), regression constant (234.027158).	y=mx	n=748 m=0.99997 $\sigma$ =8.6133 R=0.82908 F=28262053	n=710 m=0.99999 $\sigma$ =7.2951 R=0.87052 F=37386359
				y=mx+c	n=748 m=0.6873 c=523.5034 $\sigma$ =7.1454 R=0.8291 F=1640	n=712 m=0.7041 c=495.1179 $\sigma$ = 6.1215 R=0.8712 F=2235
26	End point temperature	temperature at subblance, ore added, $(1/C_f - 1/C_{sl})$ , lime, dolomite, $(C_{sl}-C_f) \cdot \Delta O_2$	Temperature model (for plant (4) data set ) temperature at subblance(0.862664316), ore added(-0.010897906), $(1/C_f - 1/C_{sl})$ (1507.172515679), lime(-0.00453730), $(C_{sl}-C_f)$ (-0.022923968), $\Delta O_2$ (8.561622479), regression constant (251.8219512).	y=mx	n=2214 m=0.99992 $\sigma$ =12.035 R=0.80602 F=41035957	n=2100 m=0.99968 $\sigma$ =10.1074 R=0.85358 F=55202061
				y=mx+c	n=2214 m=0.6498 c=573.7695 $\sigma$ =9.7052 R=0.8060 F=4101	n=2111 m=0.6607 c=555.6642 $\sigma$ =8.2886 R=0.8477 F=5384
27	End point temperature	temperature at subblance, ore added, $(1/C_f - 1/C_{sl})$ , lime, dolomite, $(C_{sl}-C_f) \cdot \Delta O_2$ (carbon calculated from carbon model No.(14)	temperature at subblance(0.881824165), ore added(-0.010025682), $(1/C_f - 1/C_{sl})$ (-766.253851801), lime(-0.000257262), $(C_{sl}-C_f)$ (-0040002643), $\Delta O_2$ (12.078419703), dolomite(-0.02135692), regression constant (221.672589).	y=mx	n=1819 m=0.99993 $\sigma$ =11.9799 R=0.8033 F=34003698	n=1723 m=0.99966 $\sigma$ =9.8743 R=0.85616 F=47425417
				y=mx+c	n=1819 m=0.6452 c=581.0997 $\sigma$ =9.6253 R=0.8033 F=3305	n=1738 m=0.6685 c=542.7269 $\sigma$ =8.2032 R=0.8515 F=4579

<sup>1</sup> n=number of data points, m= slope of curve, c=constant,  $\sigma$ =standard deviation, R=correlation coefficient, F=F-test value

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## APPENDIX-1

Various operational variables given in the sample data sets are calculated as follows.

Time of blow can be calculated as described in Chapter 3 by Eqs. (3.11) or (3.12).

$$\text{Basicity} = \frac{\text{CaO}}{\text{SiO}_2} = \frac{\text{CaO}}{\left[ \text{Si(in.HM)} \times \text{Wt.of.HM} \times \frac{60}{28} \times \frac{1}{100} \right]}$$

$$\Delta O_2 = \frac{O_2}{(\text{Wt.of.HM} \times 0.92 + \text{Wt.of.Scrap})}$$

$$\text{HotRatio} = \frac{\text{Wt.of.HM}}{\text{Wt.of.Scrap}}$$

$$\text{Slagvol} = \text{lime1} + \text{Rslag1} + \text{dolo1} + \text{dolspl1} + \text{SiO}_2$$

$$\text{Second blow additions} = \text{lime2} + \text{Rslag2} + \text{dolo2} + \text{dolo2} + \text{dolspl2}$$

Abbreviations used are :

HM =hotmetal

SBA = second blow additions

lime1 =lime added in the first blow

lime2 = lime added in the second blow

dolo1 =dolomite added in the first blow

dolo2 = dolomite added in the second blow

dolspl1 = dolomite special added in the first blow

dolspl2 = dolomite special added in the second blow

Rslag1 = return slag in yhe first blow

Rslag2 = return slag in the secon blow

ore1 =ore added in the first blow

ore2 = ore added in the second blow

O<sub>22</sub> = oxygen blown in the second blow

sample data set of plant(1)

Heat No.	Hotmetal	Si(in HM)	Scrap	O22	T <sub>SL</sub>	C <sub>SL</sub>	T <sub>f</sub>	C <sub>f</sub>	lime(kg)
	tons	(milli %)	tons	m <sup>3</sup>	°C	(milli %)	°C	(milli %)	
2179	286.8	418	47.8	1520	1636	257	1672	61	10250
2181	292.0	254	48.1	1700	1614	356	1661	70	10150
2182	299.2	200	57.7	2420	1593	607	1660	67	8510
2183	296.0	228	49.6	1390	1623	166	1655	60	9980
2184	290.3	171	45.3	1730	1602	374	1658	64	8510
2186	300.0	415	50.3	2000	1636	389	1702	59	11510
2189	300.0	289	44.0	1980	1637	356	1664	41	12000
2190	299.2	323	42.7	1980	1621	453	1666	75	9090
2191	286.0	482	58.8	1880	1591	426	1650	72	11500
2192	279.0	412	56.0	2300	1604	502	1666	62	9970
2194	300.0	288	47.7	2400	1584	424	1662	67	8750
2197	297.6	285	61.4	1950	1604	451	1665	62	8510
2198	296.6	359	54.6	2340	1612	472	1670	54	8600
2199	290.6	326	55.3	2300	1581	539	1665	49	8850
2200	290.8	338	51.5	1840	1604	339	1652	82	10540
2202	286.0	425	57.4	1990	1621	390	1667	65	10130
2203	285.0	488	54.6	2080	1582	395	1657	47	11810
2206	289.9	433	58.1	1790	1632	384	1670	83	10460
2207	292.5	478	55.4	1970	1594	505	1666	71	12500
2208	285.0	466	47.7	1160	1612	306	1646	114	13460
2210	285.0	447	47.6	1380	1622	275	1654	96	14630
2211	285.0	542	49.5	1810	1615	383	1680	61	12490
2212	284.8	436	58.6	1280	1616	256	1656	111	13070
2213	285.0	480	64.0	1700	1617	375	1672	59	11510
2214	297.2	460	55.5	1610	1602	356	1648	104	13240
2215	286.2	441	60.4	1680	1613	358	1672	69	10800
2218	285.4	447	53.7	1980	1621	386	1682	56	10230
2219	285.3	408	46.0	1620	1607	442	1663	79	9620
2220	285.0	384	57.9	1440	1614	285	1650	97	11250
2221	285.0	348	58.0	1770	1614	377	1679	71	10120
2223	285.2	636	44.5	1680	1599	234	1668	45	14220
2224	285.0	389	59.3	1280	1620	251	1653	87	11630
2225	285.0	447	63.5	1300	1622	354	1661	85	11020
2227	275.3	485	57.7	1500	1610	411	1657	82	11100
2228	281.3	454	58.5	1610	1624	409	1664	119	13060
2229	284.1	548	66.6	1320	1628	351	1666	76	12490
2230	283.8	671	72.3	1100	1608	292	1643	100	14800
2231	282.2	383	58.5	1980	1595	470	1638	77	9300
2232	280.2	375	63.8	1990	1580	442	1658	65	9210
2233	292.8	358	47.6	2100	1627	550	1671	88	10260

(continued ...)



Sample Data set of plant (1) (continued ...)

Heat No.	Rslag1 (kg)	Dolo1 (kg)	Lance Life	Lime2 (kg)	Rslag2 (kg)	Dolo2 (kg)	Ore2 (kg)	Dol spl (kg)	L11 (m)	hotratio
2179	3008	0	30	0	0	0	1004	314	227	6.0000
2181	2604	0	31	0	0	0	968	0	0	6.0707
2182	3880	0	45	0	2000	0	1004	0	234	5.1854
2183	3108	0	32	0	0	0	400	0	0	5.9677
2184	4000	0	46	0	0	0	950	0	223	6.4084
2186	3300	0	47	0	0	0	1004	0	242	5.9642
2189	4524	0	36	0	0	0	1988	1	0	6.8182
2190	3808	0	37	0	0	0	998	494	236	7.0070
2191	3306	0	38	0	0	0	508	0	231	4.8639
2192	2904	0	39	0	0	0	998	574	231	4.9821
2194	4204	0	40	0	0	0	0	0	250	6.2893
2197	3990	0	50	0	430	0	1004	0	234	4.8469
2198	5208	0	42	0	0	0	1000	994	249	5.4322
2199	2480	0	51	0	490	0	1008	0	225	5.2550
2200	3060	0	43	0	0	0	1000	0	250	5.6466
2202	3000	0	44	0	0	0	0	994	237	4.9826
2203	3390	0	53	0	0	0	498	0	217	5.2198
2206	3004	0	47	0	2004	0	308	0	237	4.9897
2207	3640	0	54	0	0	0	498	0	222	5.2798
2208	3884	0	48	0	0	0	500	0	232	5.9748
2210	4000	850	49	0	130	844	1000	0	232	5.9874
2211	3600	0	56	0	0	0	998	0	220	5.7576
2212	3848	0	50	0	0	0	0	0	237	4.8601
2213	3300	0	57	0	0	0	508	0	225	4.4531
2214	3760	0	51	0	0	0	0	0	244	5.3550
2215	3100	0	58	0	0	0	608	0	225	4.7384
2218	3004	0	53	0	1464	0	0	0	236	5.3147
2219	4320	0	60	0	0	0	608	0	214	6.2022
2220	2814	0	54	0	0	0	390	0	239	4.9223
2221	4100	0	61	0	0	0	0	0	223	4.9138
2223	4120	0	62	0	0	0	0	0	218	6.4090
2224	3302	0	56	0	0	0	510	0	242	4.8061
2225	3220	0	63	0	0	0	1018	0	223	4.4882
2227	3200	0	64	0	0	0	1008	0	0	4.7712
2228	3004	0	58	0	0	0	0	0	237	4.8085
2229	3620	0	65	0	970	0	994	0	222	4.2658
2230	4300	0	66	0	0	0	0	0	222	3.9253
2231	4370	0	59	0	0	0	1000	404	241	4.8239
2232	5090	0	67	0	0	0	0	404	222	4.3918
2233	3508	0	60	0	0	0	1000	594	229	6.1513

(continued ...)

## Sample Data set of plant (1) (continued ..)

Heat No.	Slagvol (kg)	time (sec)	SBA (kg)	Basicity	$\Delta O_2$ m <sup>3</sup> /ton.	$(UC_t - UC_{sat})$
2179	15826.9082	152	314	3.9900	4.8772	12.5024
2181	14343.3145	170	0	6.6366	5.3672	13.2779
2182	13672.2861	242	2000	8.0001	7.2681	12.9512
2183	14534.1719	139	0	4.3143	4.3178	14.3785
2184	13573.7422	173	0	4.3894	5.5382	11.1258
2186	17478.8574	200	0	3.8931	6.1293	11.5415
2189	18381.8574	198	1	4.0476	6.1875	14.1370
2190	14968.8916	198	494	4.7261	6.2271	12.5669
2191	17759.9707	188	0	4.6823	5.8400	13.9117
2192	15337.1719	230	574	3.7691	7.3558	16.3999
2194	14805.4287	240	0	4.3595	7.4143	18.5529
2197	14317.4854	195	430	5.0042	5.8176	9.2453
2198	16089.7012	234	994	3.8892	7.1456	12.8205
2199	13360.0488	230	490	3.9627	7.1284	18.7449
2200	15707.2227	184	0	3.8887	5.7674	9.4440
2202	15734.6426	199	994	4.1722	6.2087	12.1043
2203	18180.2852	208	0	4.7296	6.5657	5.5040
2206	16153.8574	179	2004	5.3592	5.5109	6.7803
2207	19136.0352	197	0	3.7733	6.0709	13.7825
2208	20189.9277	116	0	4.9120	3.7431	5.1028
2210	22209.8926	138	974	3.9264	4.4545	14.2825
2211	19400.0723	181	0	4.5195	5.8069	6.8064
2212	19578.8457	128	0	3.9932	3.9923	11.6995
2213	17741.4277	170	0	3.7421	5.2115	15.2665
2214	19929.5430	161	0	3.8567	4.8947	10.3958
2215	16604.5898	168	0	4.7971	5.1899	6.8005
2218	15967.7246	198	1464	4.7617	6.2605	11.4320
2219	16434.3359	162	0	3.6585	5.2516	17.9487
2220	16409.1426	144	0	4.8954	4.4986	7.5102
2221	16345.2852	177	0	4.0368	5.5278	8.9398
2223	22226.8691	168	0	4.7723	5.4744	5.9584
2224	17307.6777	128	0	3.7438	3.9813	10.3089
2225	16969.8926	130	0	3.6269	3.9914	6.5753
2227	17161.1543	150	0	4.0154	4.8235	10.8594
2228	18800.6465	161	0	4.0904	5.0741	13.1222
2229	19446.1465	132	970	4.5677	4.0247	9.5455
2230	23180.6387	110	0	4.1052	3.2994	9.8457
2231	15986.0557	198	404	4.2537	6.2240	14.6707
2232	16551.6074	199	404	4.4084	6.1881	8.7245
2233	16014.1943	210	594	5.1236	6.6251	10.1958

## APPENDIX-2

Sample Data set of plant (2)

(for details of variables see Appendix 1)

Heat No.	Hotmetal (kg)	Si (in HM %)	Scrap (kg)	Csl. %	O 22 (m <sup>3</sup> )	Ore2 (kg)
11127	322000	0.205	9704	0.210	1692	0
11153	323100	0.306	10921	0.222	1742	0
11165	325300	0.326	9798	0.347	1951	6
11167	322700	0.270	9430	0.388	2520	0
11186	319700	0.205	11534	0.520	2339	0
11202	330400	0.320	9497	0.478	2260	0
11213	314100	0.438	14483	0.362	1618	0
11214	330900	0.507	14016	0.339	1545	0
11264	331100	0.342	13695	0.391	1531	0
11282	334200	0.266	9488	0.328	2038	0
11305	316500	0.356	10147	0.310	1697	0
11306	330500	0.272	10104	0.431	2027	0
11311	325800	0.382	10208	0.506	1995	0
11326	325400	0.240	10985	0.633	2225	0
11330	319800	0.667	13601	0.325	1972	0
11331	333100	0.246	12027	0.349	1921	0
11332	330900	0.266	10992	0.265	1824	0
11351	332100	0.315	11998	0.269	1718	0
11366	328200	0.567	13315	0.428	2062	0
11371	336000	0.283	9122	0.344	1930	0
11386	313700	0.241	9711	0.393	1947	0
11389	316200	0.647	15242	0.416	1733	0
11398	330900	0.372	12855	0.397	2137	0
11425	314500	0.279	10169	0.354	2153	0
11426	315800	0.318	13743	0.494	2180	0
11427	323400	0.472	14665	0.360	2139	0
11490	330700	0.302	12200	0.290	1833	0
11511	329300	0.336	11931	0.446	2030	0
11533	331800	0.300	9397	0.309	1676	0
11534	335100	0.350	11243	0.390	2012	0
11535	316600	0.303	9595	0.289	1522	0
11555	325200	0.305	9591	0.355	1821	0
11556	321700	0.442	11684	0.287	1783	0
11565	321000	0.478	13539	0.539	2339	10
11569	320400	0.448	11472	0.405	2136	0
11574	328500	0.329	11646	0.431	2189	0
20019	326600	0.277	9591	0.288	1417	0
20056	325200	0.233	10960	0.436	2257	0
20095	323300	0.316	9495	0.340	1830	0
20096	325200	0.337	9504	0.326	1827	0

(continued ...)

Sample Data set of plant (2) (continued ...)

Heat No.	$C_r$ (%)	time (sec)	Basicity	$T_r$ (°C)	SBA (kg)	$T_{sl}$ (°C)
11127	0.061	169.2	6.8604	1662	0	1602
11153	0.035	174.2	5.1548	1661	0	1600
11165	0.060	195.1	4.3116	1683	0	1613
11167	0.044	252.0	5.0507	1676	0	1571
11186	0.057	233.9	8.2128	1664	0	1575
11202	0.052	226.0	4.1918	1671	7	1595
11213	0.075	161.8	4.9127	1654	0	1591
11214	0.099	154.5	3.8988	1648	0	1599
11264	0.086	153.1	5.6440	1660	0	1611
11282	0.049	203.8	4.9807	1683	0	1602
11305	0.060	169.7	4.2026	1667	0	1611
11306	0.048	202.7	5.2452	1702	0	1614
11311	0.082	199.5	3.8277	1651	0	1578
11326	0.100	222.5	6.5641	1675	0	1594
11330	0.057	197.2	2.9756	1692	0	1612
11331	0.052	192.1	6.8494	1670	62	1589
11332	0.063	182.4	5.8278	1662	2	1600
11351	0.072	171.8	5.3522	1663	3	1605
11366	0.054	206.2	3.3391	1670	0	1595
11371	0.050	193.0	4.4768	1677	0	1599
11386	0.080	194.7	5.9943	1666	0	1599
11389	0.072	173.3	3.4768	1668	0	1610
11398	0.047	213.7	4.8735	1675	0	1599
11425	0.049	215.3	5.4083	1656	0	1578
11426	0.082	218.0	6.3863	1669	0	1598
11427	0.058	213.9	4.4834	1671	0	1597
11490	0.056	183.3	5.7007	1678	4	1622
11511	0.072	203.0	5.0321	1653	0	1570
11533	0.052	167.6	4.4055	1675	0	1602
11534	0.053	201.2	4.4735	1699	0	1609
11535	0.058	152.2	4.6676	1663	0	1615
11555	0.048	182.1	4.5125	1659	0	1592
11556	0.042	178.3	3.8346	1670	0	1614
11565	0.041	233.9	4.1178	1678	0	1579
11569	0.047	213.6	3.7297	1663	0	1578
11574	0.068	218.9	5.0287	1662	0	1588
20019	0.090	141.7	4.9474	1697	0	1636
20056	0.046	225.7	6.7501	1687	0	1593
20095	0.057	183.0	4.3372	1669	0	1604
20096	0.049	182.7	4.0470	1682	0	1611

### APPENDIX-3

Sample Data set of plant (3) (for details of variables see Appendix 1)

Heat No.	C <sub>r</sub> %	Time sec	Basicity	SBA (kg)	T <sub>SL</sub> °C	T <sub>r</sub> °C
30631	0.054	155.67	3.3112	0	1590	1679
30634	0.047	82.07	3.7524	0	1610	1650
30637	0.043	128.00	5.5732	0	1607	1688
30639	0.081	129.20	4.0937	2	1603	1669
30640	0.057	118.53	6.6491	0	1620	1691
30646	0.057	154.13	4.2895	0	1586	1666
30647	0.068	113.40	3.7188	0	1605	1657
30654	0.066	108.13	3.9241	0	1612	1676
30665	0.142	137.07	3.7164	0	1607	1675
30667	0.056	129.07	3.4888	0	1605	1671
30675	0.088	147.53	4.3149	0	1586	1670
30680	0.067	124.33	5.6757	0	1614	1680
30682	0.055	129.07	3.7215	0	1594	1667
30683	0.068	124.13	5.6294	0	1622	1687
30712	0.103	140.67	4.8219	0	1607	1690
30713	0.064	145.60	4.3692	0	1606	1687
30726	0.064	121.33	2.8124	0	1639	1698
30753	0.075	132.00	6.1096	0	1594	1661
30764	0.076	157.27	4.5839	0	1586	1667
30767	0.047	150.53	4.4429	0	1589	1683
30777	0.057	125.13	5.5283	0	1598	1660
30806	0.052	148.13	4.5990	0	1616	1680
30811	0.046	129.07	3.6186	0	1611	1673
30812	0.052	125.47	2.7817	0	1624	1692
30818	0.043	134.53	3.0713	0	1616	1680
30821	0.059	134.20	3.0031	0	1622	1684
30823	0.049	180.40	4.8102	0	1631	1729
30844	0.067	134.07	5.3248	0	1622	1683
30875	0.041	147.47	3.9531	0	1627	1717
30876	0.053	133.40	3.4251	0	1607	1678
30888	0.051	127.27	5.1502	0	1637	1689
30890	0.052	121.80	5.2489	0	1622	1695
30897	0.053	147.40	4.7865	0	1589	1673
30898	0.055	144.33	5.6425	0	1600	1674
30910	0.038	156.47	4.4567	0	1619	1692
30915	0.061	126.67	6.3197	0	1602	1663
30921	0.082	154.40	4.0927	0	1591	1676
30958	0.061	159.47	3.8174	0	1605	1692
30992	0.043	140.27	2.9743	0	1582	1661
31013	0.055	110.87	4.5456	0	1607	1670

(continued ...)

Sample Data set of plant (3) (continued .. )

Heat No.	HM (kg)	Si (in HM) %	Scrap (kg)	C <sub>sl</sub> %	O 22 m <sup>3</sup>	Ore 2 (kg)
30631	316500	0.516	11588	0.477	2335	0
30634	313900	0.433	10929	0.122	1231	0
30637	317100	0.285	10793	0.277	1920	0
30639	327000	0.384	11015	0.359	1938	0
30640	327600	0.204	9522	0.281	1778	0
30646	326000	0.317	9499	0.440	2312	0
30647	326400	0.386	10040	0.377	1701	0
30654	326200	0.468	12837	0.354	1622	0
30665	315500	0.526	13216	0.636	2056	0
30667	324200	0.464	11246	0.389	1936	0
30675	313700	0.364	10558	0.546	2213	0
30680	328300	0.237	9463	0.297	1865	0
30682	328900	0.363	9521	0.417	1936	0
30683	318800	0.265	10191	0.375	1862	0
30712	316000	0.295	9632	0.521	2110	0
30713	331000	0.311	9638	0.377	2184	0
30726	321100	0.857	16584	0.335	1820	0
30753	333200	0.241	10513	0.276	1980	0
30764	324800	0.406	12953	0.416	2359	0
30767	314100	0.364	10885	0.359	2258	0
30777	331600	0.294	11549	0.275	1877	0
30806	324300	0.400	12784	0.362	2222	8
30811	330400	0.368	9428	0.322	1936	0
30812	330400	0.717	14121	0.341	1882	3
30818	334500	0.602	13253	0.287	2018	0
30821	329300	0.571	12100	0.349	2013	0
30823	331600	0.495	16919	0.537	2706	0
30844	333700	0.393	14964	0.298	2011	0
30875	332400	0.476	13403	0.321	2212	0
30876	315700	0.503	11655	0.436	2001	0
30888	333400	0.453	16668	0.247	1909	0
30890	314400	0.353	12483	0.351	1827	0
30897	327900	0.402	13520	0.400	2211	0
30898	333700	0.351	14162	0.397	2165	0
30910	330500	0.435	13730	0.441	2347	0
30915	329000	0.213	9490	0.229	1900	0
30921	313500	0.433	11905	0.642	2316	0
30958	328400	0.411	11041	0.429	2392	0
30992	324700	0.560	11589	0.375	2104	0
31013	314500	0.306	9374	0.374	1663	0

**APPENDIX-4**

Sample Data set of plant (4)

(for details of variables see Appendix 1)

Heat No.	O 22 (m <sup>3</sup> )	T <sub>f</sub> (°C)	Scrap (kg)	Ore2 (kg)	HM (kg)	lime (kg)
515991	1380	1661	190000	602	217510	6310
515992	1150	1650	190300	1597	217420	4650
515993	1150	1648	183300	0	224705	8080
515994	2340	1614	181800	2804	223420	15460
515995	1660	1626	187200	979	214305	12370
515996	1330	1639	183100	1329	218635	13550
515997	1310	1659	175300	0	214450	21930
515998	1130	1649	169200	0	214600	19700
515999	1420	1658	181200	1006	215600	13260
516000	1550	1629	173100	0	212555	19640
516001	1090	1639	175200	0	214900	10380
516002	780	1657	189700	1183	222300	8570
516003	1510	1637	189400	0	222700	10320
516004	1510	1644	192900	1101	226820	13050
516005	1260	1637	192900	1499	228615	4540
516006	1330	1625	183900	1136	216710	7820
516008	120	1654	188100	0	220725	9390
516009	1210	1632	188100	1515	218330	11140
516010	1330	1633	187100	1821	221015	7620
516011	1690	1639	189600	2950	222215	9640
516012	1520	1604	189300	2252	222905	8660
516013	1640	1636	187200	2467	219505	7990
516014	1250	1614	188700	1039	221720	9230
516015	0	1634	188400	1809	221920	12660
516016	2120	1617	186600	0	223340	16720
516018	1280	1663	183100	3738	221945	4470
516019	1090	1641	185400	3236	219320	5540
516020	1180	1628	182700	2383	220420	7490
516021	1610	1629	190300	3025	223990	6070
516022	1080	1646	181500	2082	219010	6760
516023	1270	1639	179000	2268	217705	7690
516024	910	1643	179900	670	217555	4100
516025	1360	1655	181300	1482	218960	4780
516026	1180	1622	183400	1192	222625	5320
516027	1450	1625	183300	972	216735	8090
516028	1620	1629	183500	1677	219780	13070
516029	1680	1622	178600	1683	217260	8490
516030	1540	1641	186000	2049	216210	8190
516031	1680	1607	180000	600	222410	17840
516032	1210	1634	188400	0	223610	10340

(continued ...)

## Sample Data set of plant (4) (continued ..)

Heat No.	T <sub>sl.</sub> ° C	Si in HM %	Cr %	C <sub>sl.</sub> %	Time (sec)
515991	1584	0.463	0.044	0.487	190.3361
515992	1612	0.169	0.046	0.377	158.6791
515993	1584	0.581	0.031	0.151	153.5346
515994	1557	0.585	0.034	0.764	314.2064
515995	1550	0.511	0.044	0.401	232.3791
515996	1579	0.553	0.032	0.250	182.4959
515997	1565	0.837	0.031	0.296	183.2595
515998	1577	0.861	0.035	0.217	157.9683
515999	1583	0.598	0.032	0.450	197.5881
516000	1552	0.779	0.042	0.474	218.7669
516001	1580	0.657	0.039	0.273	152.1638
516002	1612	0.555	0.049	0.250	105.2632
516003	1547	0.586	0.082	0.709	199.7178
516004	1567	0.582	0.051	0.628	165.3435
516005	1586	0.336	0.042	0.462	184.1170
516006	1571	0.362	0.056	0.576	180.5307
516008	1637	0.499	0.077	0.077	228.1574
516009	1584	0.327	0.070	0.499	224.1407
516010	1583	0.280	0.040	0.537	169.1322
516011	1583	0.473	0.060	0.589	173.0158
516012	1574	0.594	0.067	0.462	149.0972
516013	1579	0.482	0.033	0.474	215.6346
516014	1573	0.528	0.038	0.250	147.9384
516015	1561	0.325	0.037	0.537	175.0075
516016	1523	0.654	0.092	0.984	125.4855
516018	1628	0.388	0.041	0.589	186.3354
516019	1622	0.399	0.054	0.462	159.0118
516020	1602	0.613	0.073	0.589	200.7059
516021	1580	0.478	0.046	0.550	221.1302
516022	1608	0.462	0.041	0.365	231.9801
516023	1601	0.592	0.054	0.499	213.6811
516024	1601	0.244	0.045	0.296	162.3362
516025	1598	0.281	0.034	0.450	234.8309
516026	1572	0.267	0.034	0.273	205.6386
516027	1561	0.493	0.038	0.537	237.0572
516028	1573	0.552	0.059	0.628	231.1207
516029	1559	0.600	0.050	0.709	207.5133
516030	1580	0.601	0.043	0.589	205.7707
516031	1551	0.626	0.065	0.576	156.6082
516032	1548	0.399	0.036	0.330	226.8765

(continued ...)



Sample Data set of plant (4) (continued ...)

Heat No.	dolo2 (kg)	Hotratio	Basicity	lime. + dolomite.	$\Delta O_2$ m <sup>3</sup> /ton	$(C_r - C_{sl})$	$(1/C_r - 1/C_{sl})$
515991	2820	7.8189	3.3474	9130	6.3445	477	-0.0021
515992	2370	7.4336	6.7474	7020	5.2893	367	-0.0027
515993	4330	4.7984	3.5406	12410	5.1178	141	-0.0066
515994	2120	4.6735	6.7837	17580	10.4735	754	-0.0013
515995	3580	7.8326	6.0346	15950	7.7460	391	-0.0025
515996	3760	5.7943	6.2450	17310	6.0832	240	-0.0040
515997	4260	4.8966	6.9749	26190	6.1087	286	-0.0034
515998	4070	4.0190	6.3106	23770	5.2656	207	-0.0046
515999	3730	5.8452	5.7107	16990	6.5863	440	-0.0022
516000	4130	4.7950	6.7969	23770	7.2922	464	-0.0021
516001	4100	4.8000	4.2083	14480	5.0721	263	-0.0037
516002	4200	6.0997	3.7986	12770	3.5088	240	-0.0040
516003	4060	6.0470	5.4245	17110	6.7804	699	-0.0014
516004	3140	5.4801	3.2688	7680	6.6573	618	-0.0016
516005	3150	6.0693	5.4818	10970	5.5114	452	-0.0022
516006	4440	5.9209	6.7878	12060	6.1372	566	-0.0017
516008	4000	6.0382	5.0163	13640	5.5421	489	-0.0020
516009	4170	6.0779	4.1324	12160	6.0177	527	-0.0019
516010	4290	5.9905	4.3232	13520	7.6052	579	-0.0017
516011	3120	5.1577	2.9363	7590	6.8190	452	-0.0022
516012	3410	5.4052	3.4949	8950	7.4714	464	-0.0021
516013	2940	5.8916	3.1141	9010	5.6377	240	-0.0040
516014	3550	5.1709	3.7621	10310	9.4923	974	-0.0010
516015	3270	4.9311	3.3866	10960	5.7672	579	-0.0017
516016	2390	4.9972	4.3588	6490	4.9699	452	-0.0022
516018	2350	5.0361	4.3786	7130	5.3534	579	-0.0017
516019	2380	4.9037	5.0700	7700	7.1878	540	-0.0018
516020	3830	5.3754	4.1778	11920	4.9313	355	-0.0027
516021	1530	5.2730	6.0215	14600	5.8336	489	-0.0020
516022	3890	4.9066	3.6973	12380	4.1829	286	-0.0034
516023	3860	6.6667	3.4190	12050	6.2112	440	-0.0022
516024	3520	5.6071	6.4191	13860	5.3004	263	-0.0037
516025	3390	5.7066	7.2260	18320	6.6902	527	-0.0019
516026	2980	6.2561	7.5838	16760	7.3710	618	-0.0016
516027	3620	6.2145	9.4463	24050	7.7327	699	-0.0014
516028	3900	4.9429	2.6490	9610	7.1227	579	-0.0017
516029	2950	6.7071	2.7488	9200	7.5536	566	-0.0017
516030	2880	6.7082	2.8634	8640	5.4112	320	-0.0030
516031	3020	6.6585	3.1760	10330	7.8277	440	-0.0022
516032	3800	5.6585	3.1862	10250	6.8546	355	-0.0027